Latest Results From MicroBooNE

Weak Interactions and Neutrinos 2017

Kazuhiro Terao @ Columbia University
on behalf of
MicroBooNE Collaboration

Nevis Laboratories
Columbia University

μBooNE

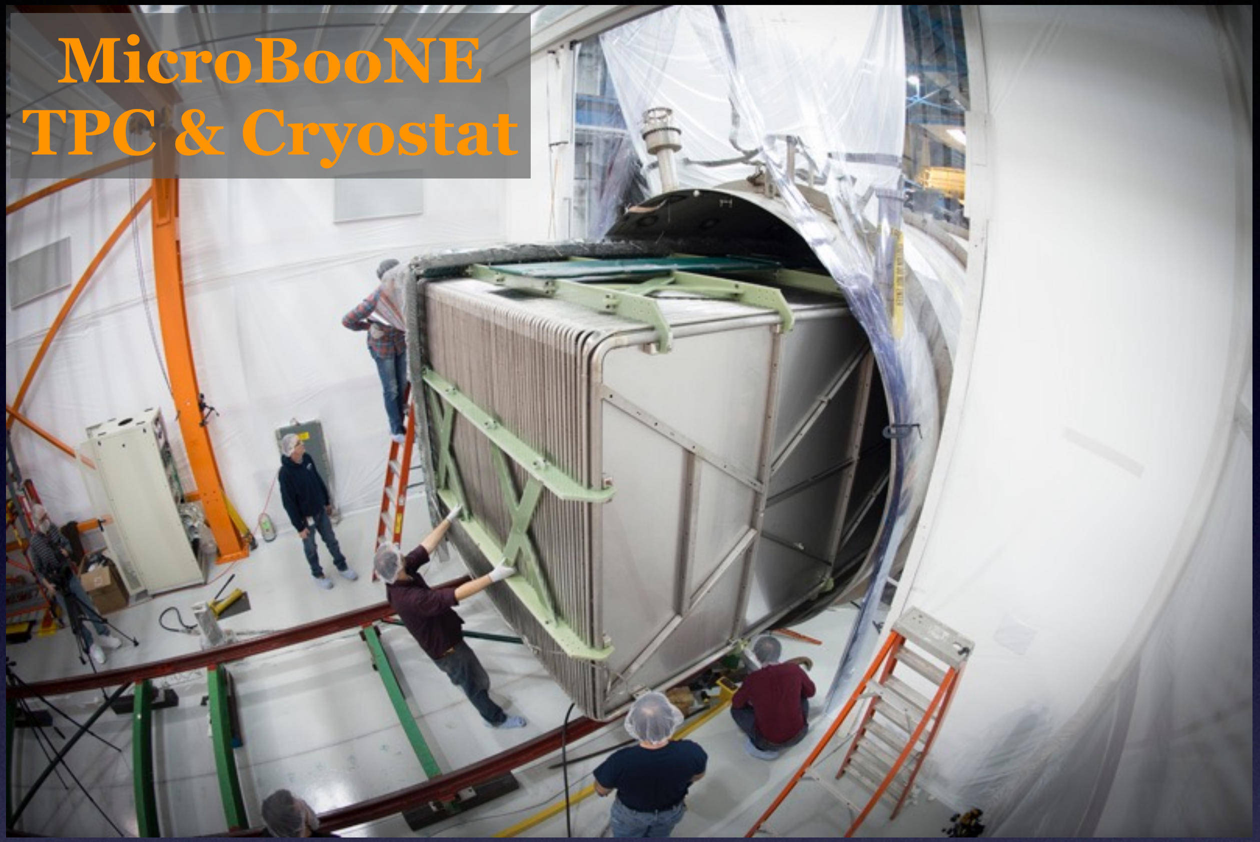
Latest Results From MicroBooNE

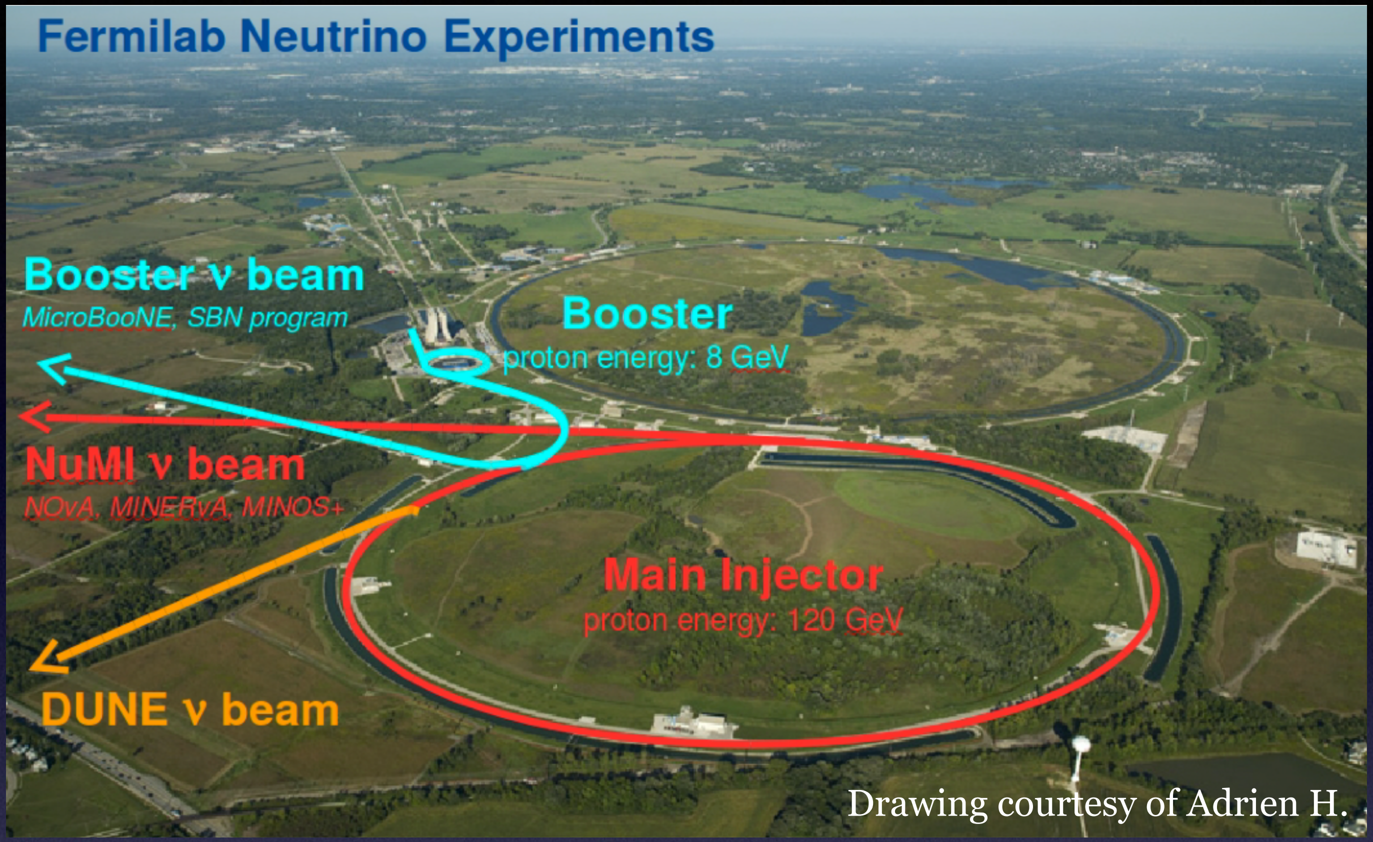
Weak Interactions and Neutrinos 2017

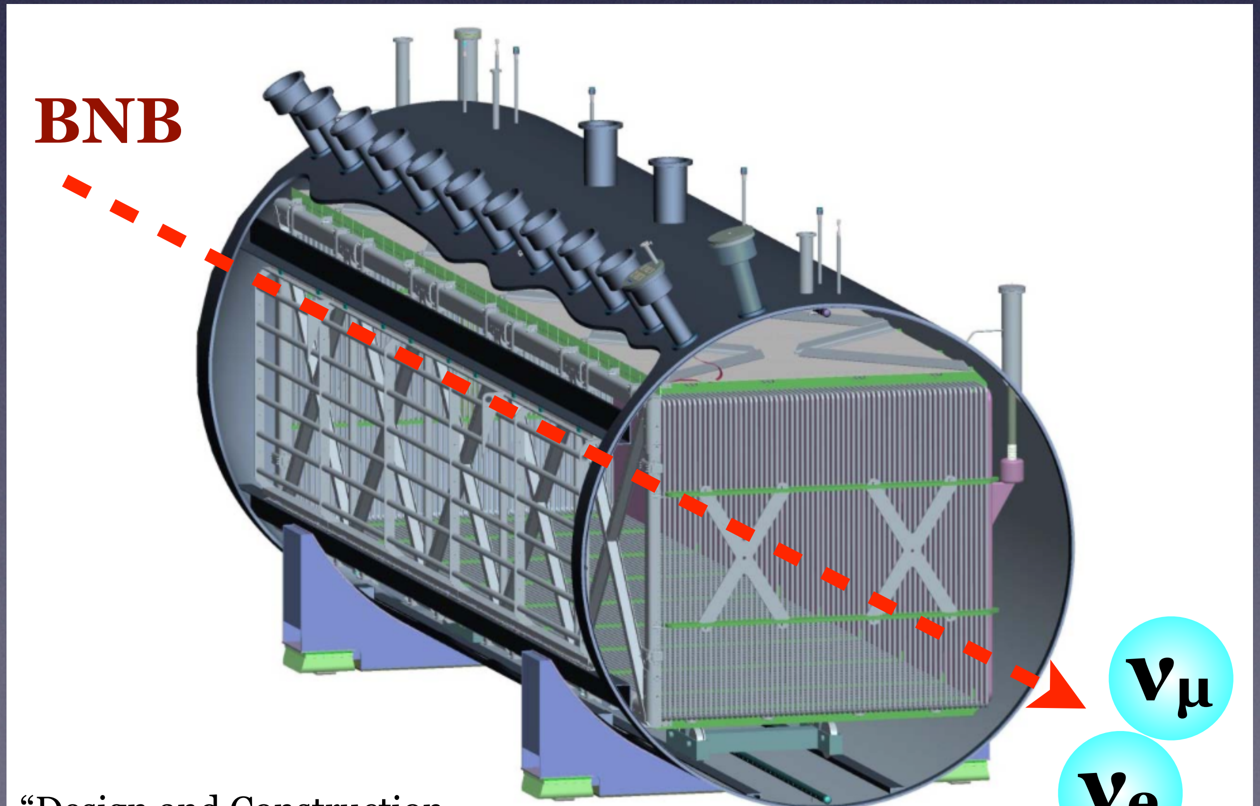
Outline

- MicroBooNE: short baseline experiment
- Current status and latest results
- Wrap-up

MicroBooNE: Introduction





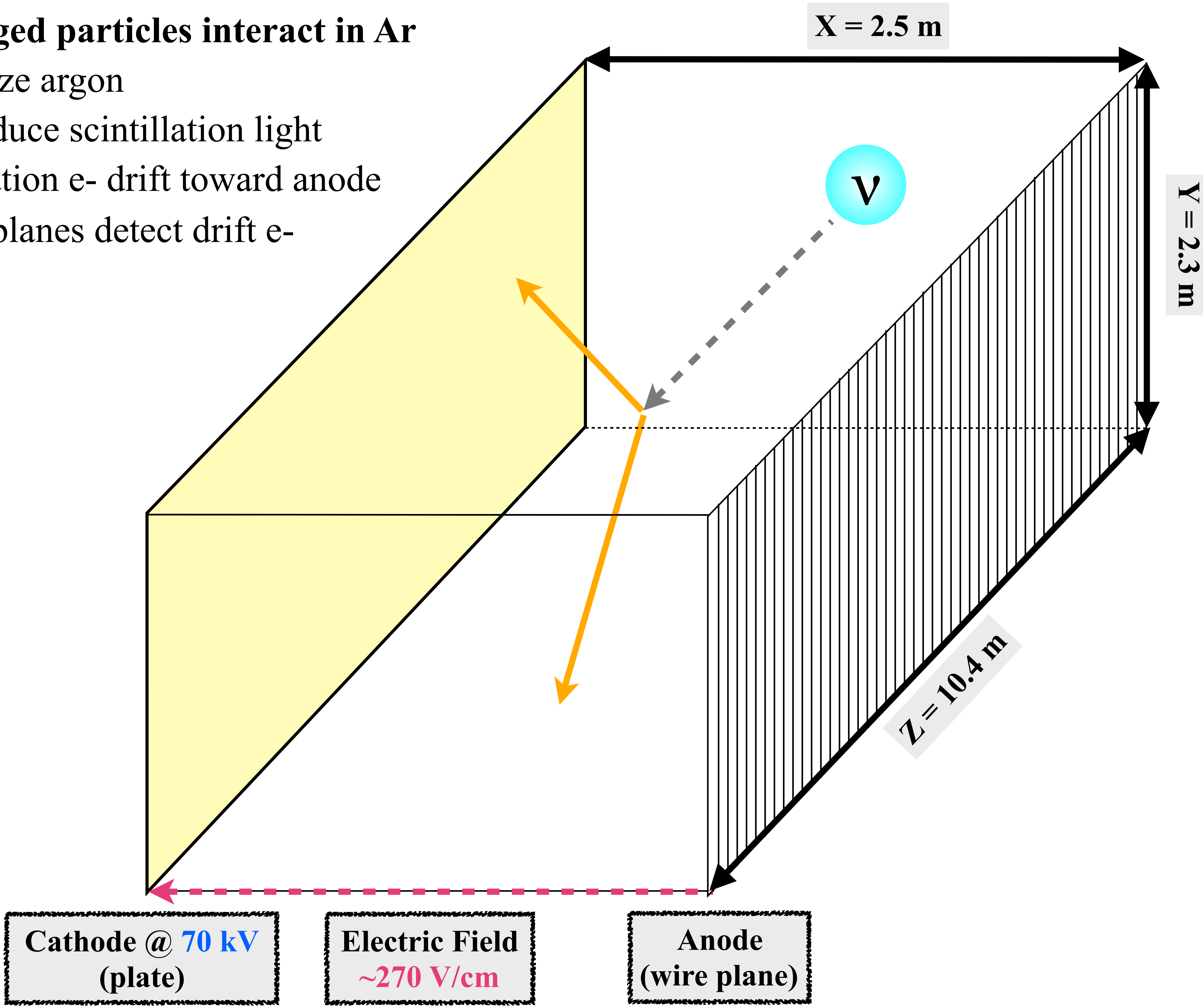


"Design and Construction of MicroBooNE detector" (JINST 12, P02017)

- **Short baseline (1m/MeV)** $\nu_\mu \Rightarrow \nu_e$ **oscillation**
- **Booster neutrino beam**
  - neutrino energy *O* (1 GeV)
- **LArTPC detector**
  - 90 tonnes TPC active volume

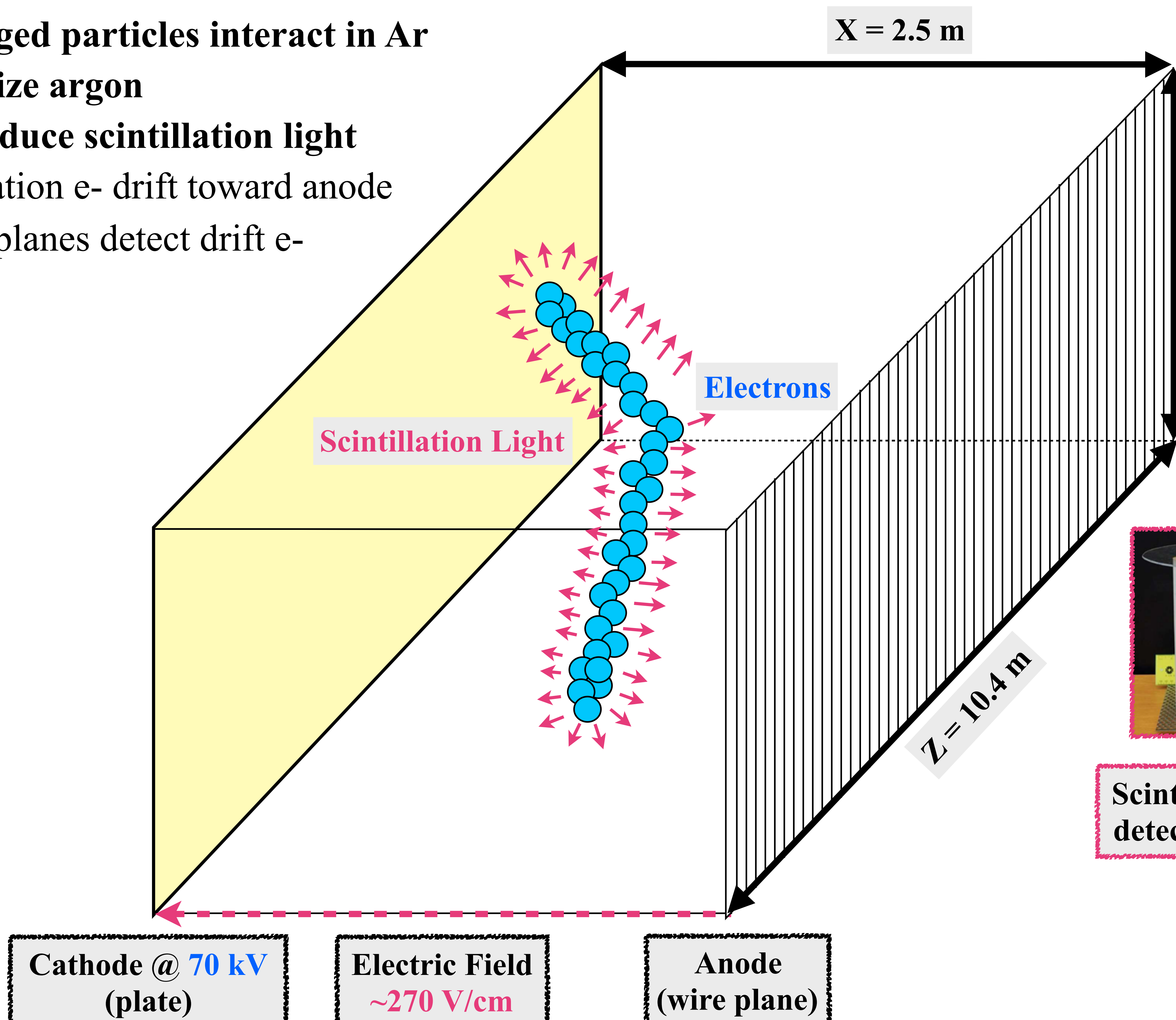
How LArTPCs Work (I)

1. **Charged particles interact in Ar**
   - Ionize argon
   - Produce scintillation light
2. Ionization e- drift toward anode
3. Wire planes detect drift e-



How LArTPCs Work (II)

1. **Charged particles interact in Ar**
   - **Ionize argon**
   - **Produce scintillation light**
2. Ionization e- drift toward anode
3. Wire planes detect drift e-

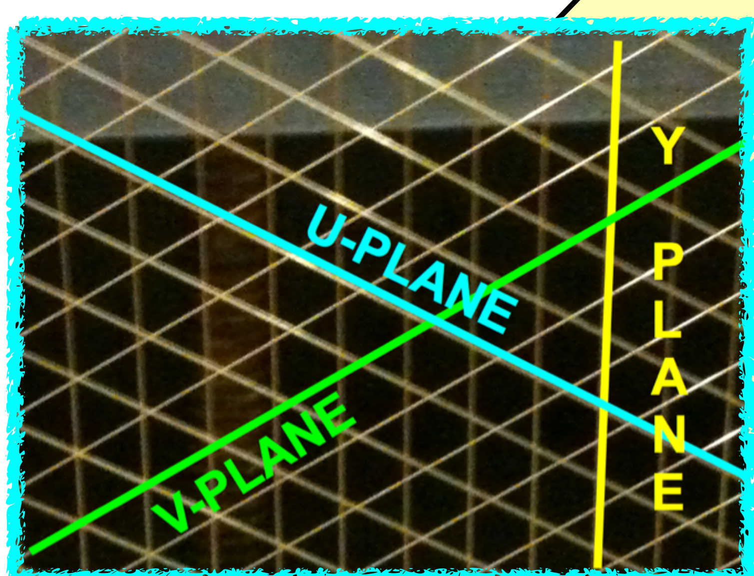


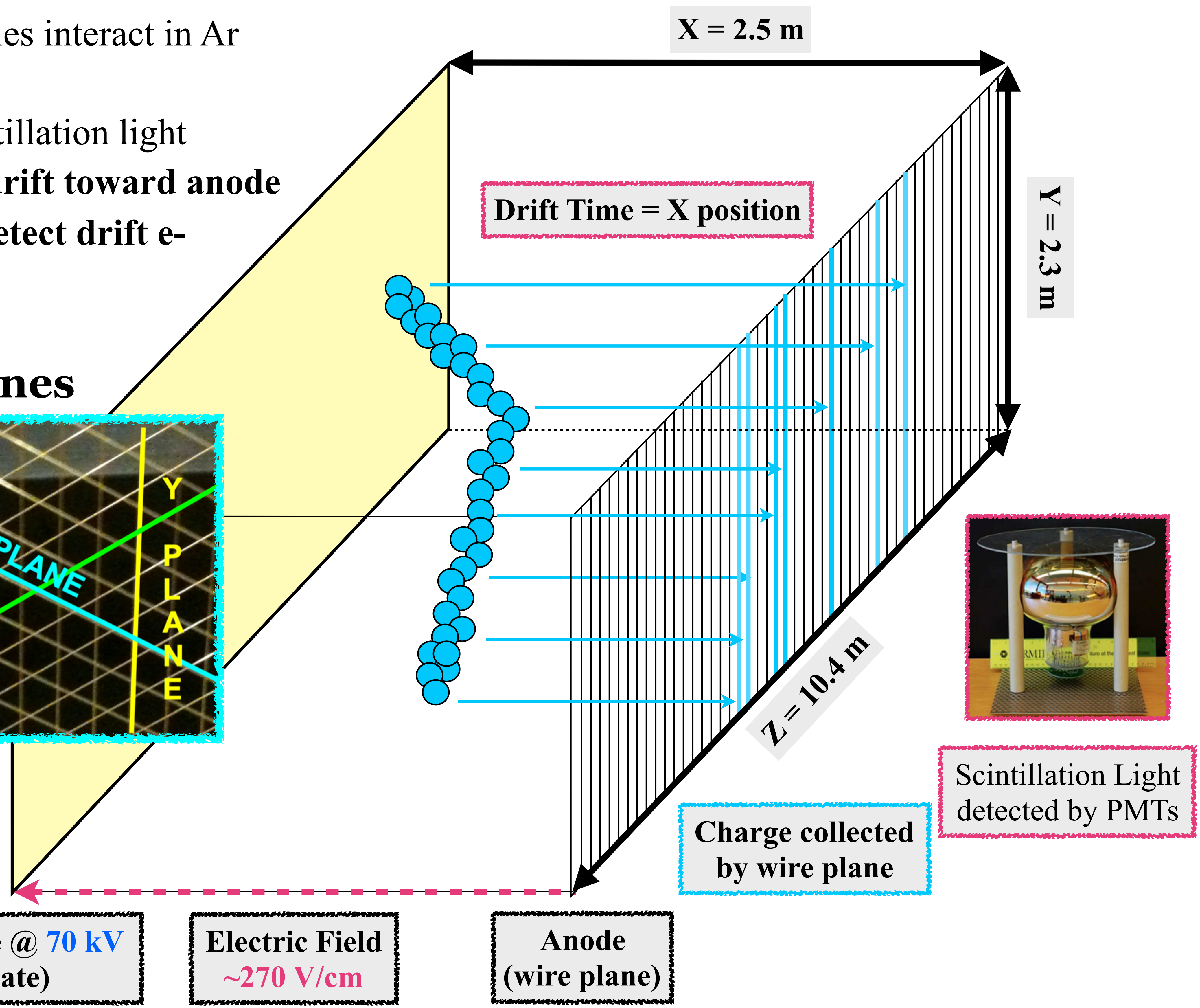
Scintillation Light
detected by PMTs

How LArTPCs Work (III)

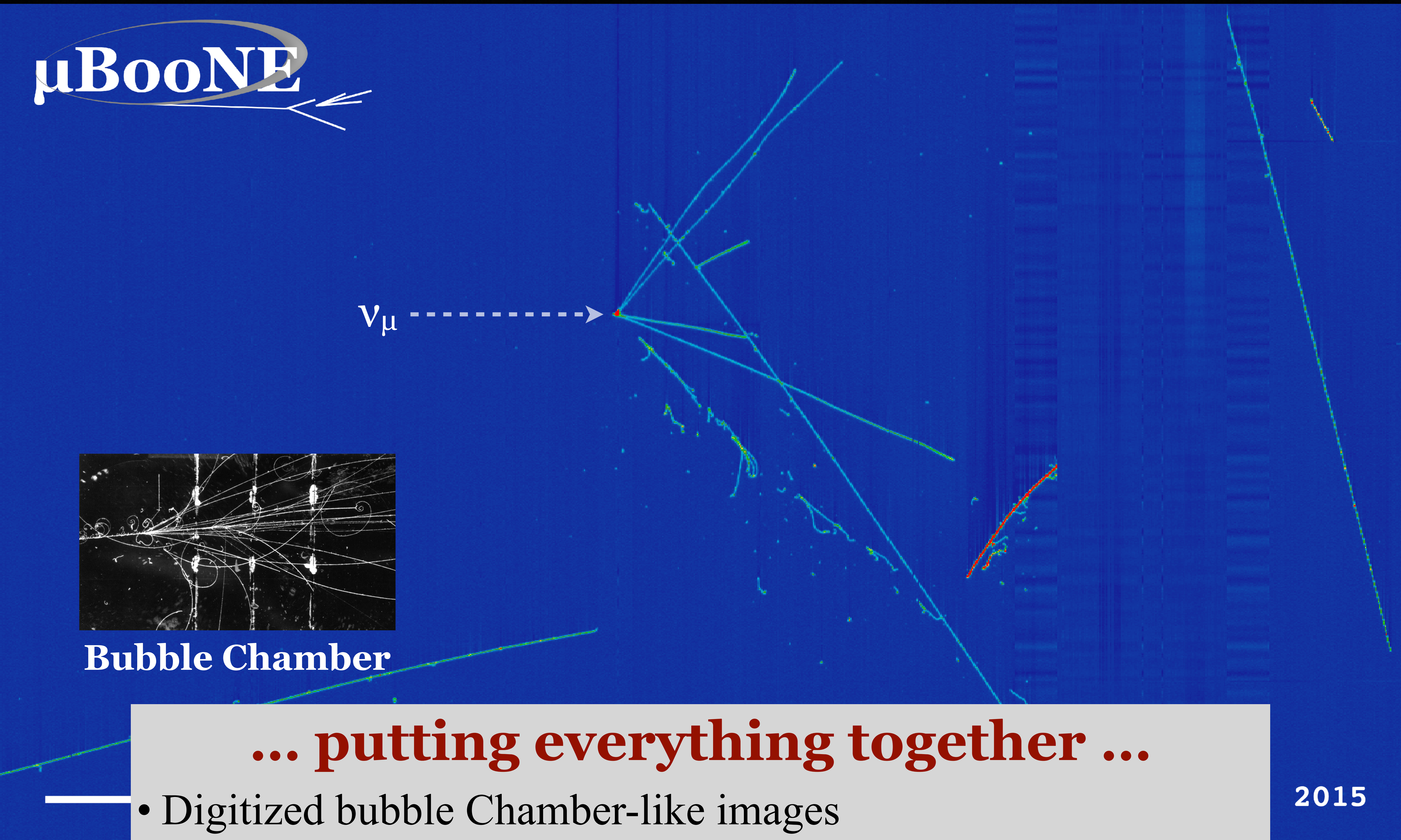
1. Charged particles interact in Ar
    - Ionize argon
    - Produce scintillation light
2. **Ionization e- drift toward anode**
3. **Wire planes detect drift e-**

Three Wire Planes





What Our Data Looks Like



Bubble Chamber

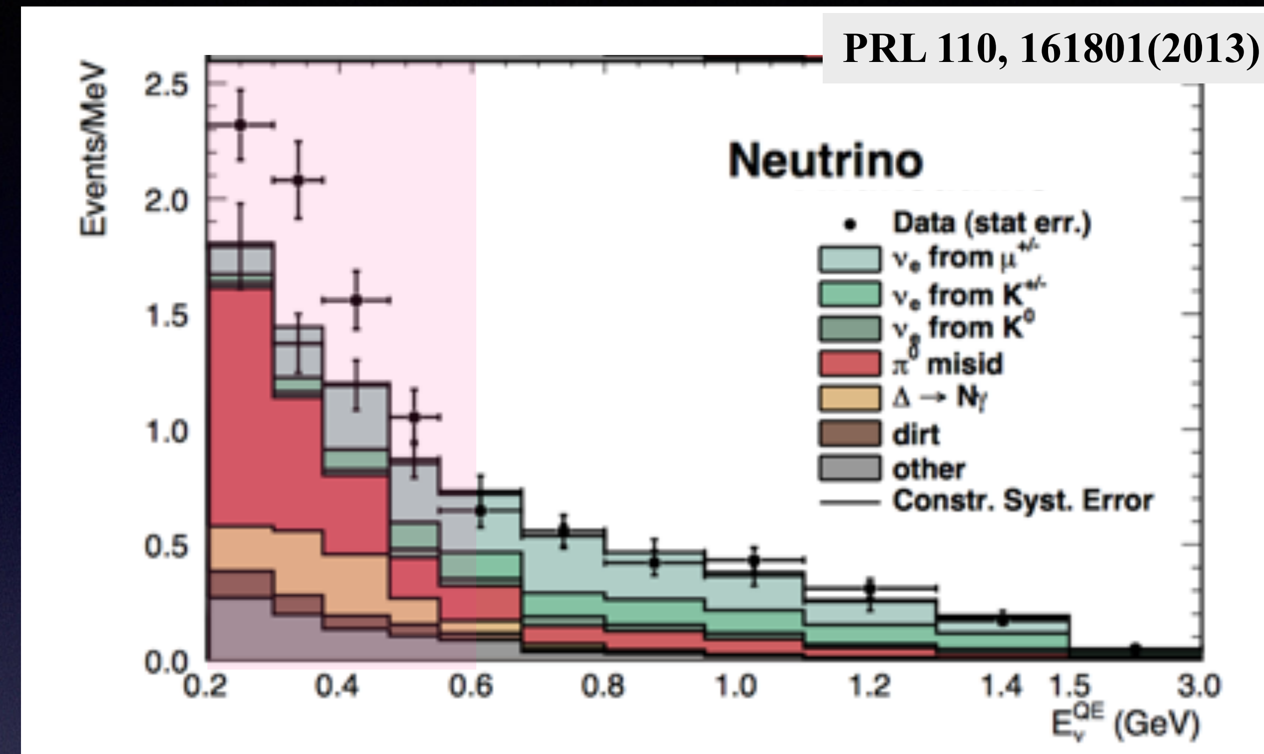
... putting everything together ...

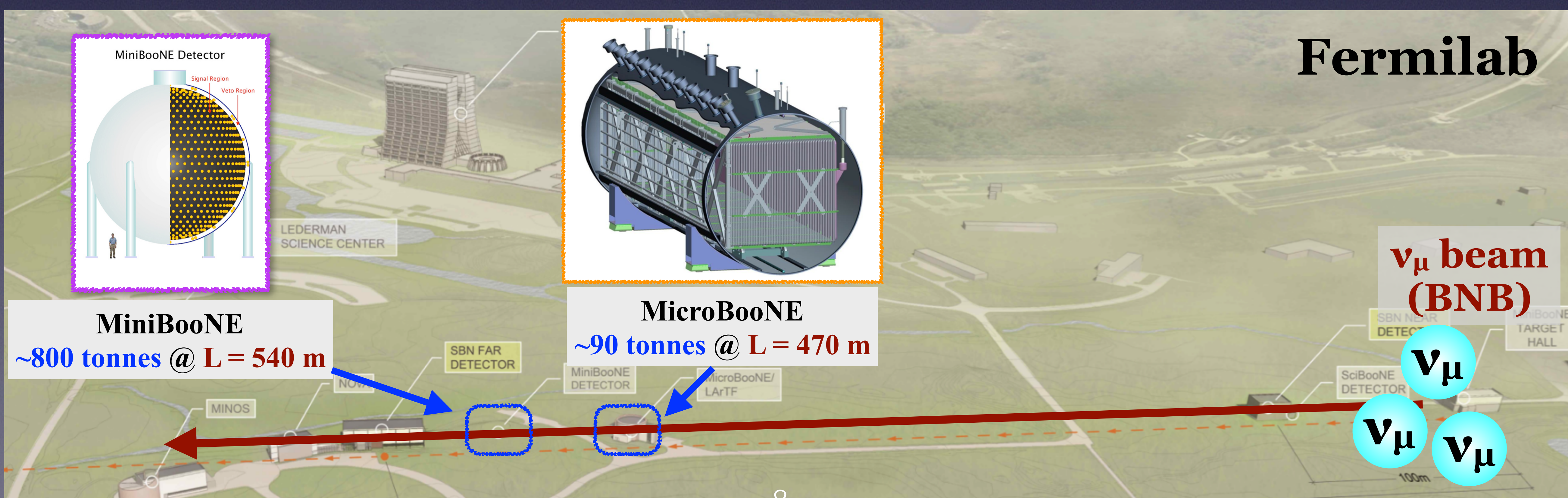
- Digitized bubble Chamber-like images
- Calorimetric measurement + scalability to a large mass

MicroBooNE: Physics Goals

Address the nature of ν_e like excess seen by MiniBooNE

- Same beam, similar baseline
  - Do we see the excess?
- Different detector: **LArTPC**
  - Is excess γ or e^- ?

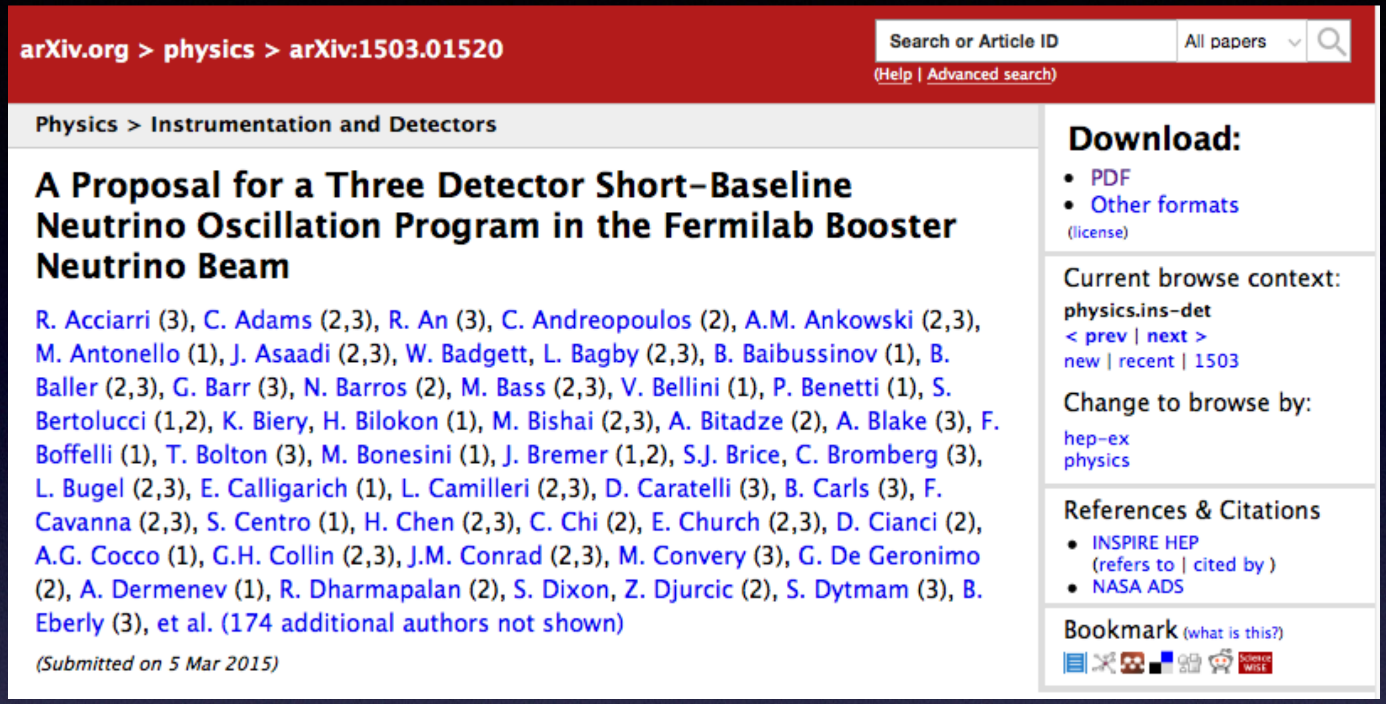




MicroBooNE in the SBN Program

Search for a short baseline oscillation signal (SBN program)

- SBND (near detector)
  - High precision ν-Ar XS
- ICARUS (far detector)
  - 6 times larger than UB!


arXiv.org > physics > arXiv:1503.01520

Search or Article ID | All papers

(Help | Advanced search)

Physics > Instrumentation and Detectors

A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

R. Acciarri (3), C. Adams (2,3), R. An (3), C. Andreopoulos (2), A.M. Ankowski (2,3), M. Antonello (1), J. Asaadi (2,3), W. Badgett, L. Bagby (2,3), B. Baibussinov (1), B. Baller (2,3), G. Barr (3), N. Barros (2), M. Bass (2,3), V. Bellini (1), P. Benetti (1), S. Bertolucci (1,2), K. Biery, H. Bilokon (1), M. Bishai (2,3), A. Bitadze (2), A. Blake (3), F. Boffelli (1), T. Bolton (3), M. Bonesini (1), J. Bremer (1,2), S.J. Brice, C. Bromberg (3), L. Bugel (2,3), E. Calligarich (1), L. Camilleri (2,3), D. Caratelli (3), B. Carls (3), F. Cavanna (2,3), S. Centro (1), H. Chen (2,3), C. Chi (2), E. Church (2,3), D. Cianci (2), A.G. Cocco (1), G.H. Collin (2,3), J.M. Conrad (2,3), M. Convery (3), G. De Geronimo (2), A. Dermenev (1), R. Dharmapalan (2), S. Dixon, Z. Djurcic (2), S. Dytmam (3), B. Eberly (3), et al. (174 additional authors not shown)

(Submitted on 5 Mar 2015)

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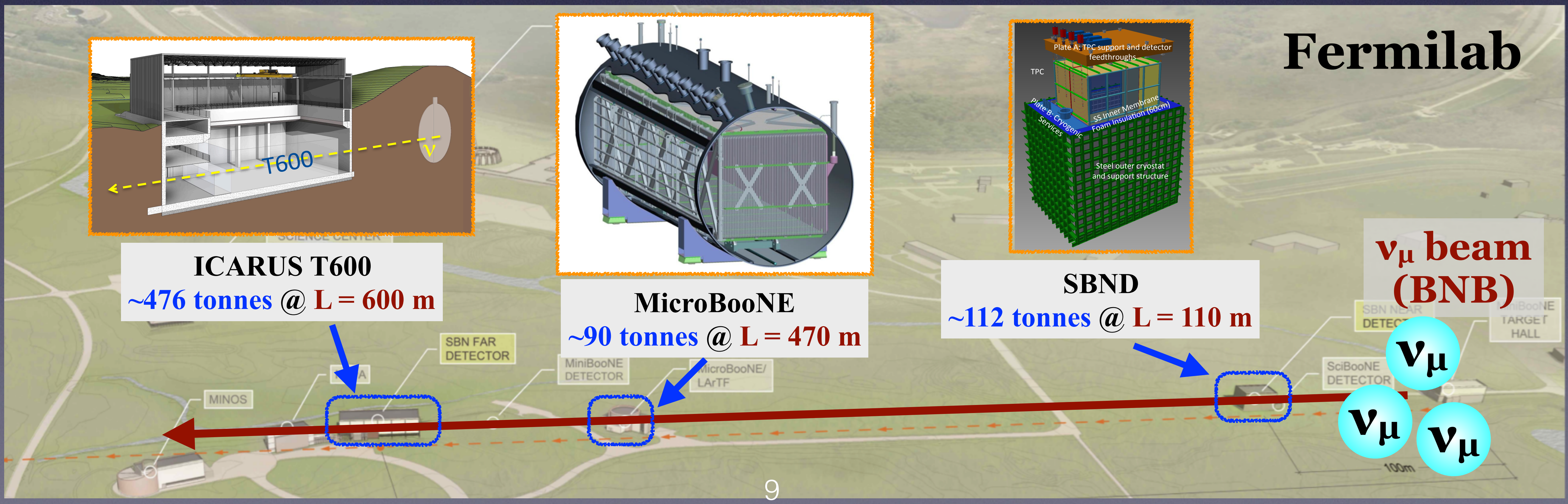
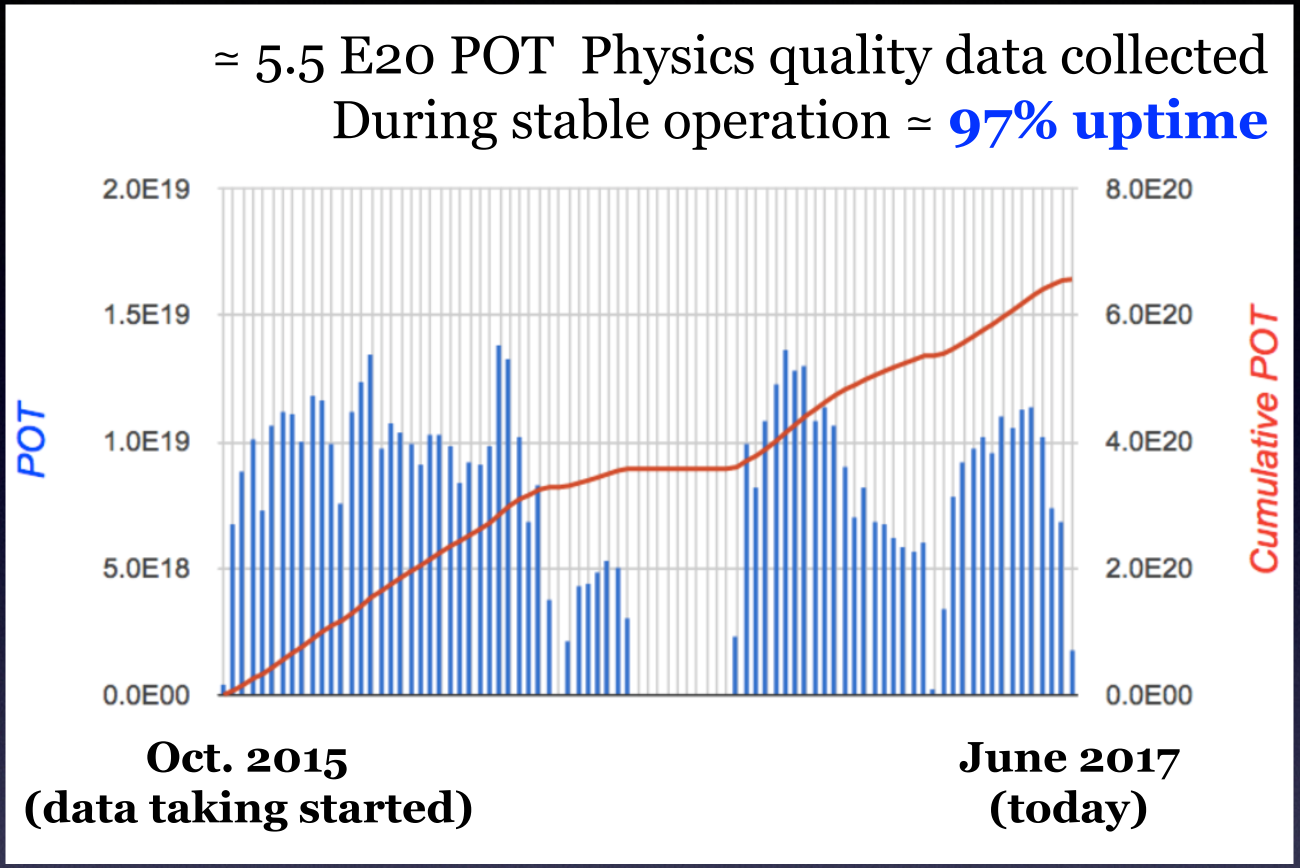


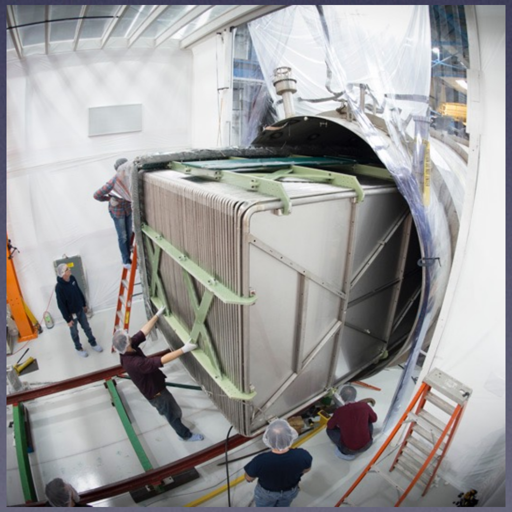
MicroBooNE LArTPC R&D

Detector R&D for future large scale LArTPC experiments

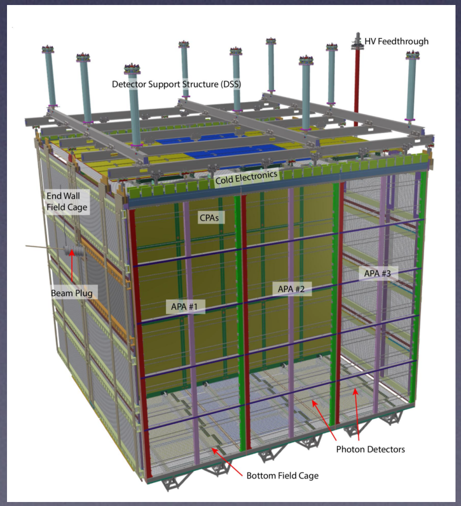
- Large scale detector
  - Construction & operation
  - Detector calibration
- Data reconstruction/analysis
  - Efficient ν_e & ν_μ search!



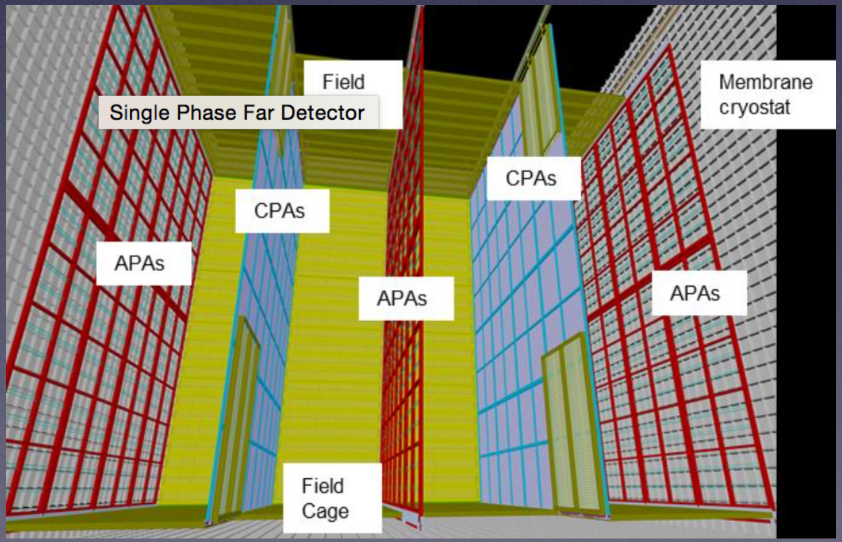
ArgoNeuT
0.3 ton (2008)



MicroBooNE
~170 tonnes (2015)



ProtoDUNE (SP)
~770 tonnes (2017)



DUNE (SP) Module
10 k tonnes (~2024)

Latest Results
From
MicroBooNE
Weak Interactions and Neutrinos
2017

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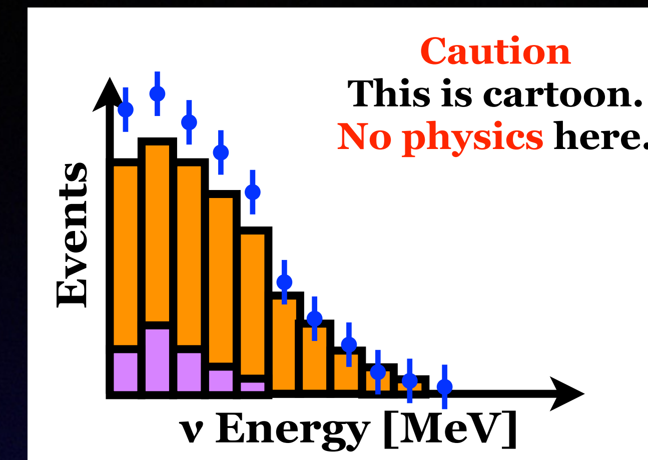
Effort Toward Physics Goals

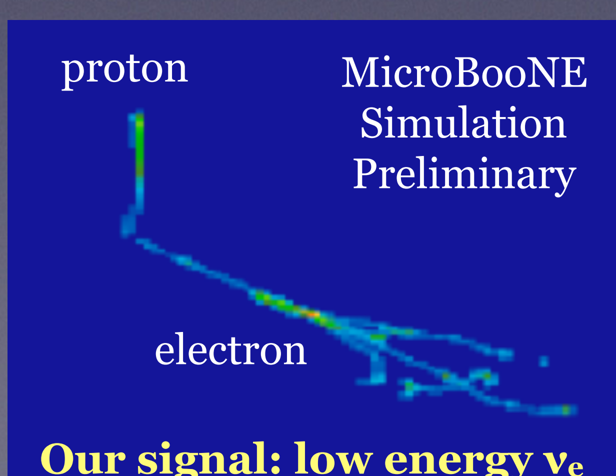


Energy/momentum reconstruction

Particle & event ID

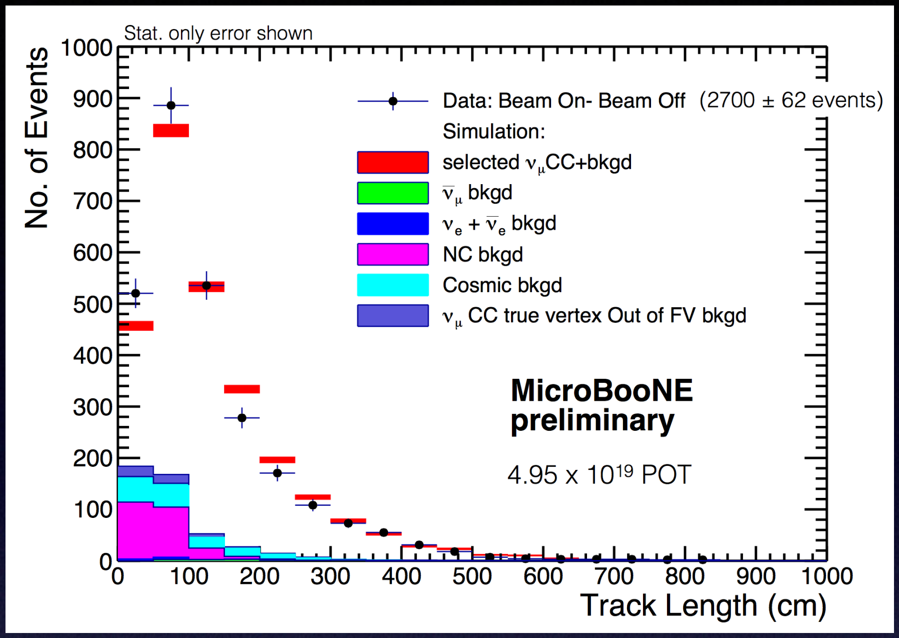
Automated 2D/3D event reconstruction

Detector response calibration

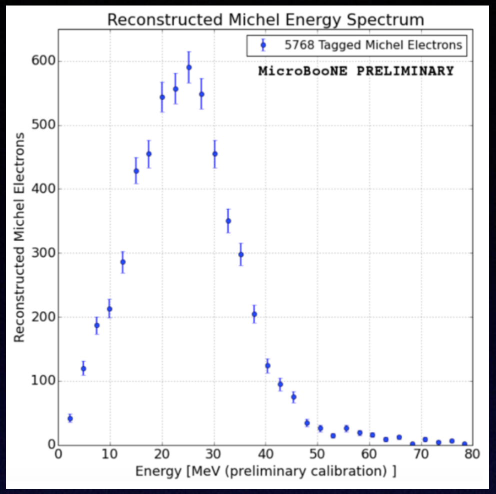


slide design, courtesy of A. Schukraft

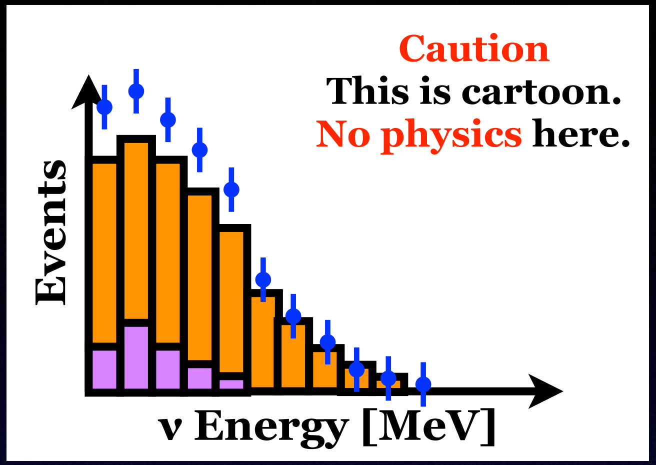
Where We Were (Neutrino 2016)

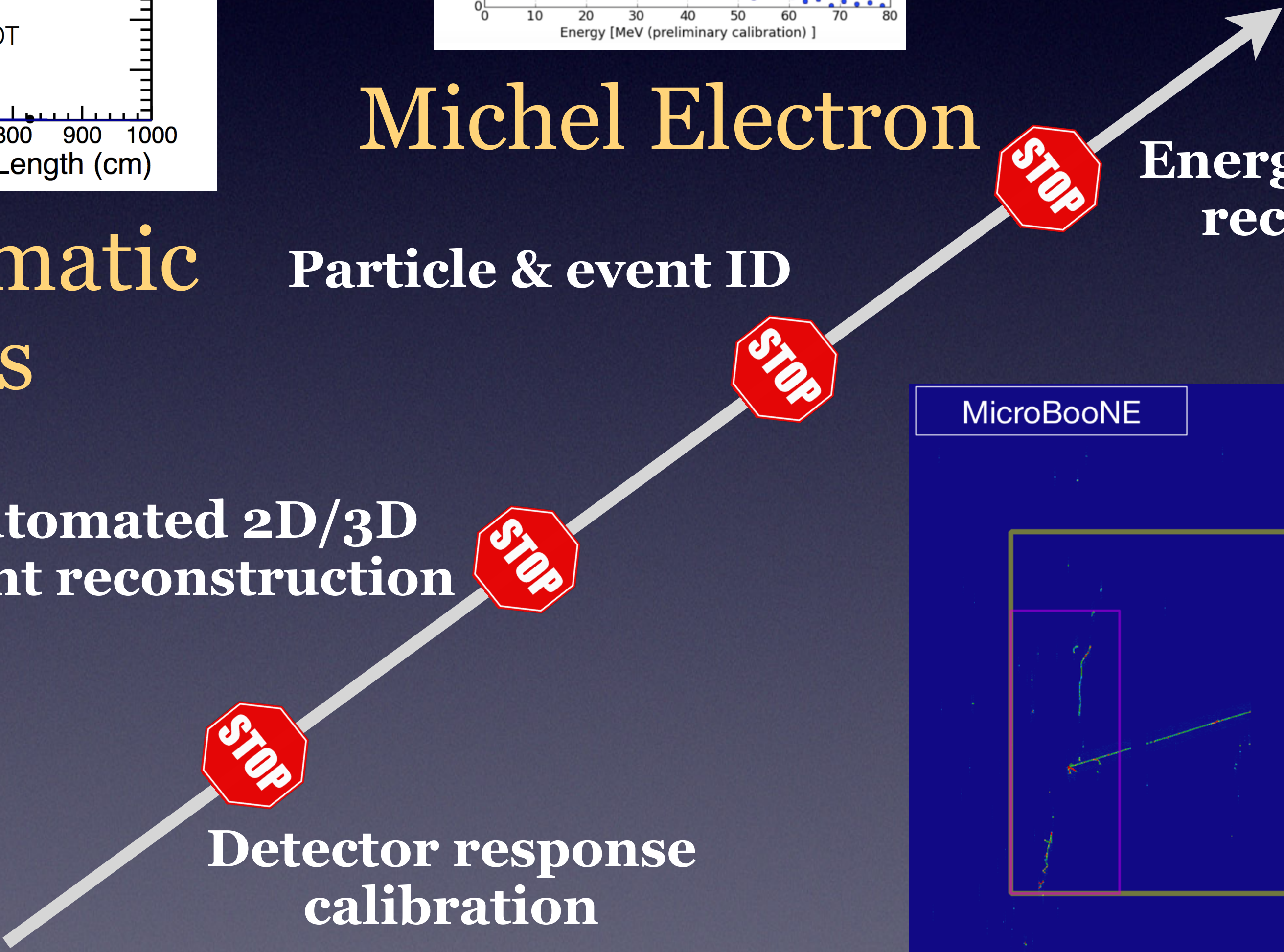


First CC ν_μ kinematic distributions



Michel Electron





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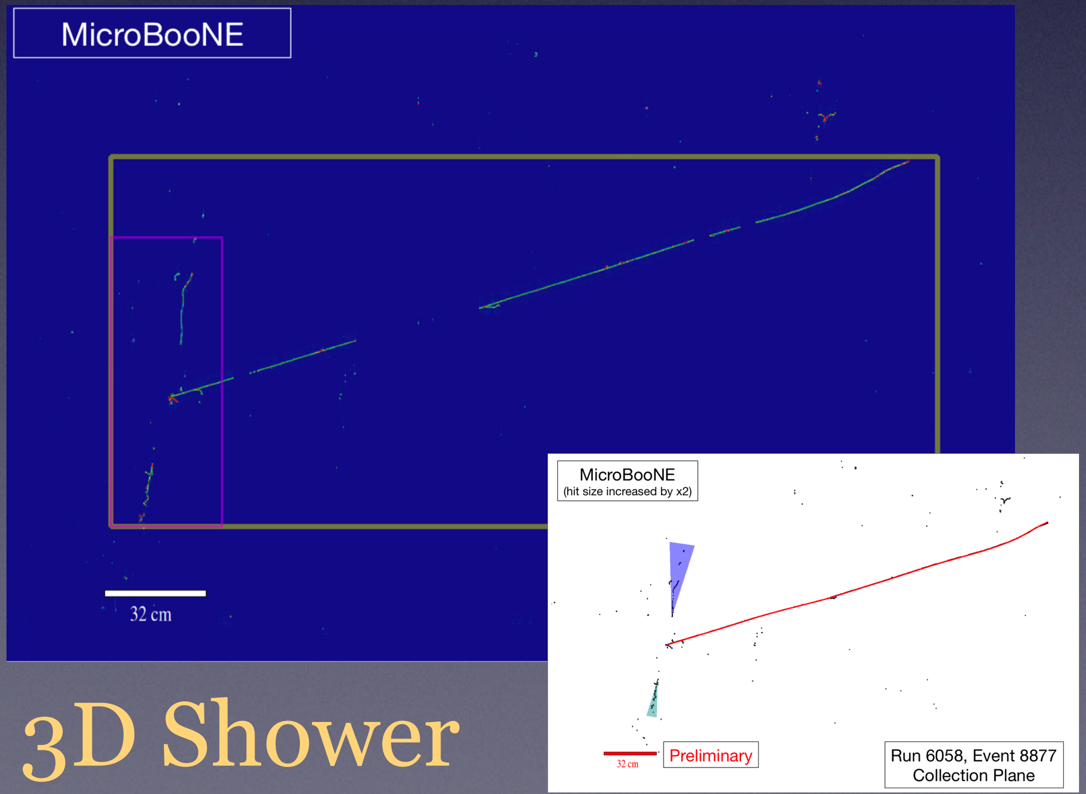
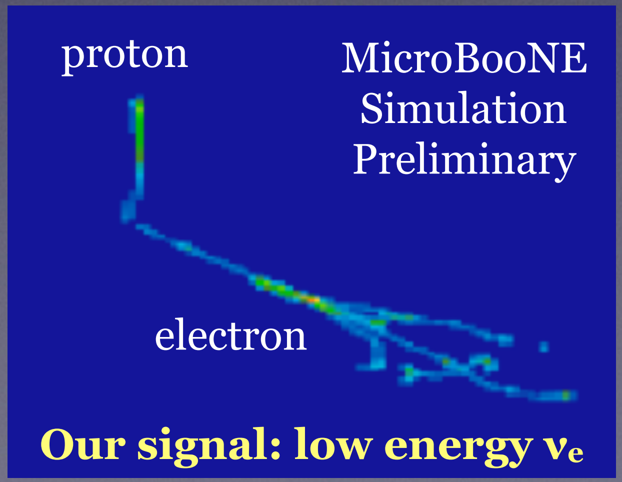
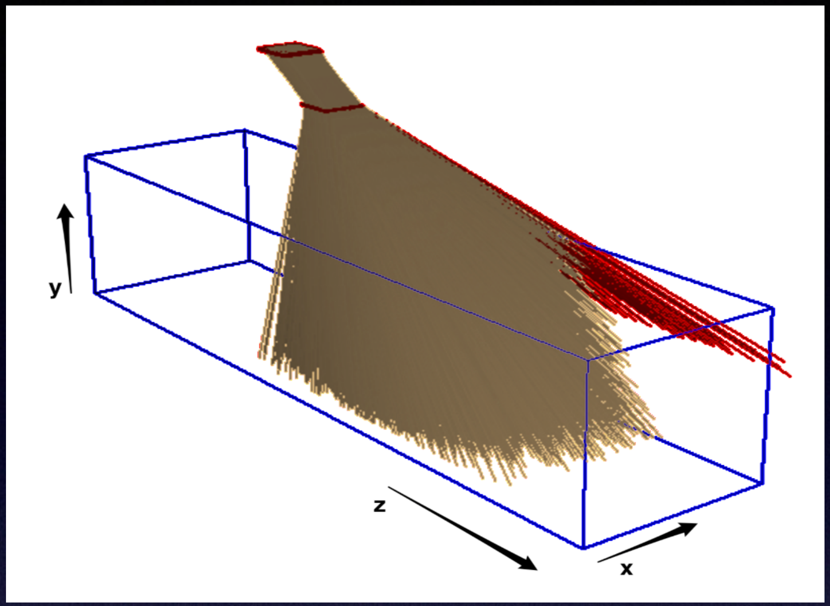


3D Shower Reconstruction (CCπ^0)



Cosmic Ray Background Study/Mitigation

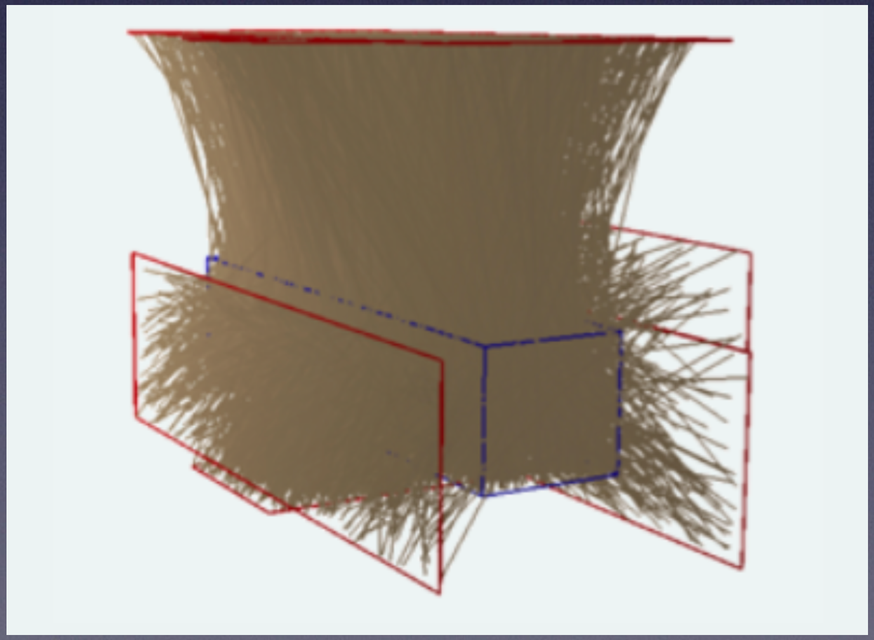


Muon Counter System
(what we have had)

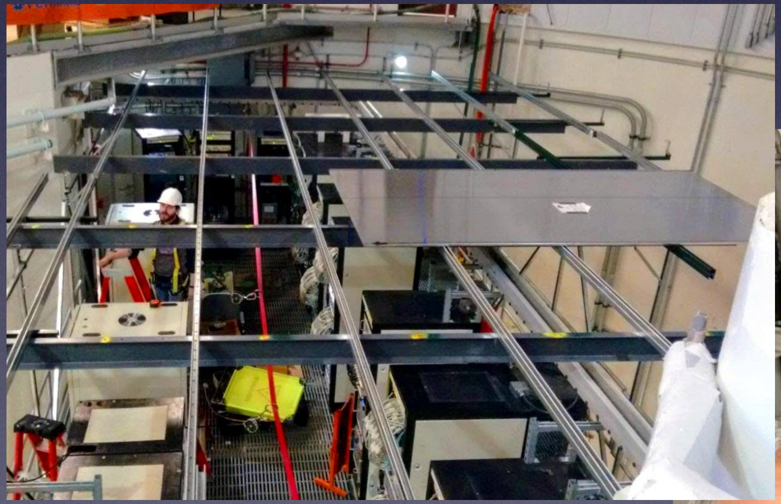
Cosmic Ray Tracker (new!)

- Scintillator strips + SiPM
  - designed by University of Bern
- Covers ~85% of cosmic rays
  - **cosmic rejection** (neutrino search)
  - **detector response** study
  - **reconstruction efficiency** study

See Roberto S's talk on Friday!

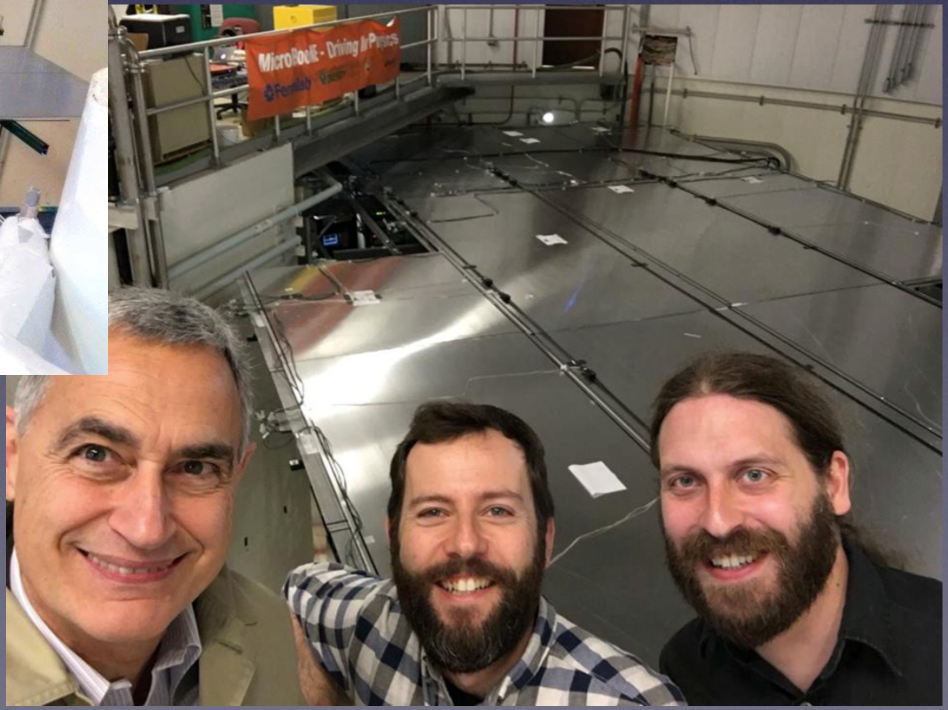


Cosmic Ray Tracker
(covers wider regions)

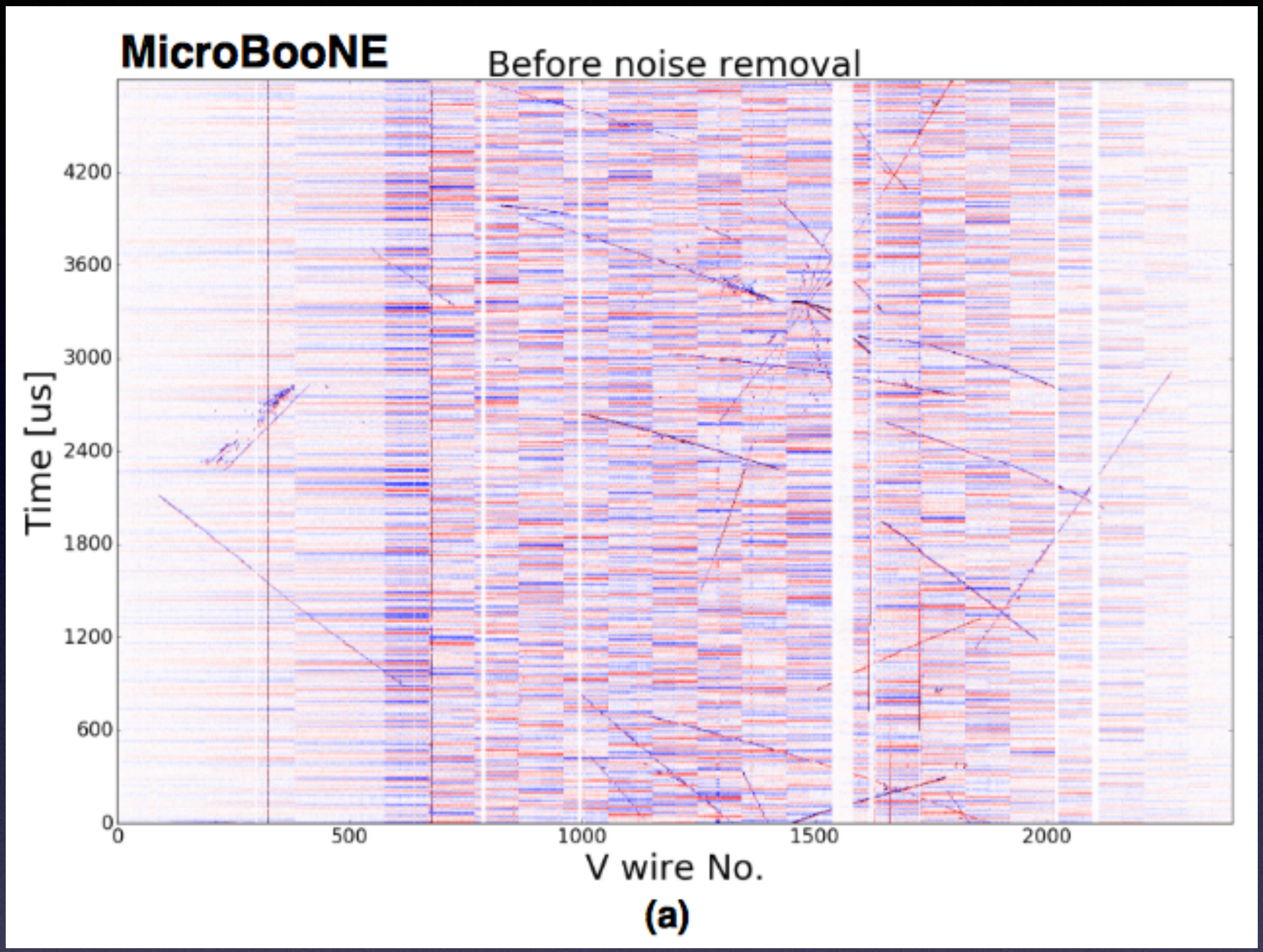


(during installation)

Completed panels covering above the detector



Results on Electronics Noise Filtering



Before **After**

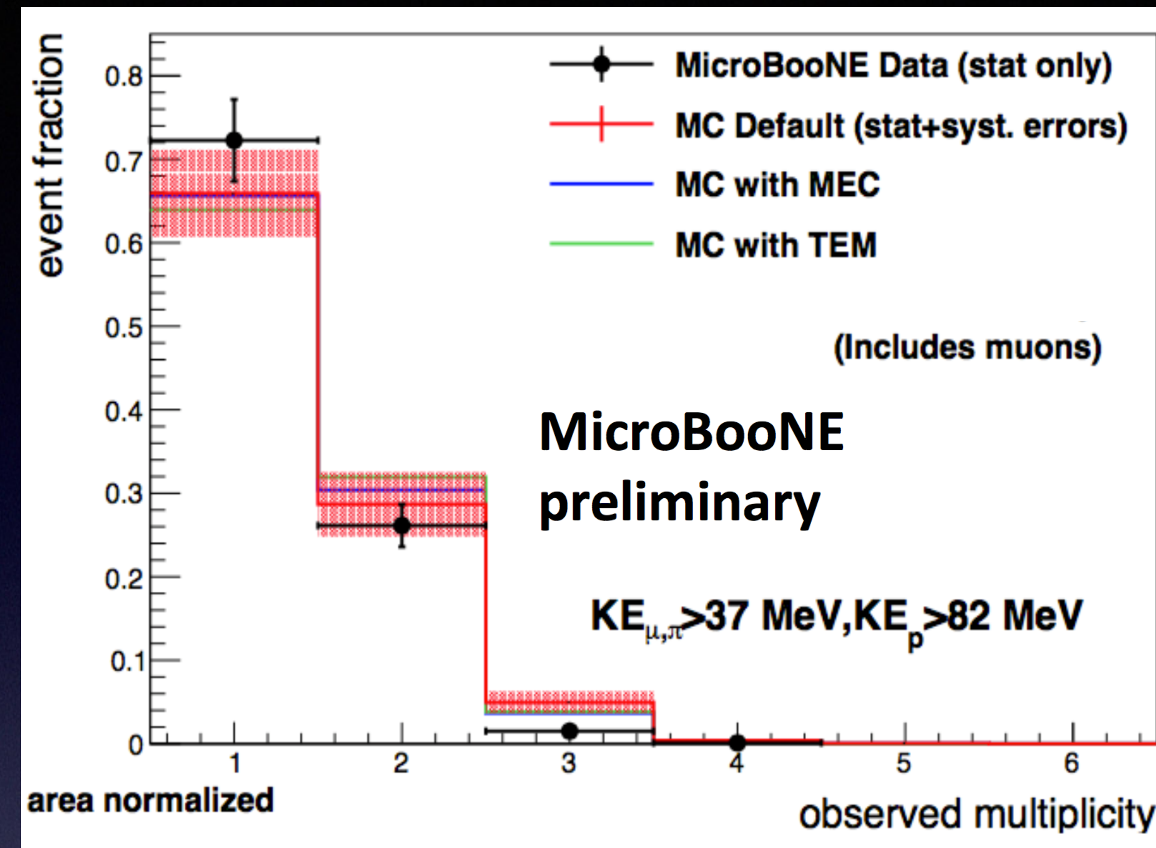
Noise Characterization & Filtering

- arXiv: 1705.07341
- The very first step in high quality physics reconstruction
- Crucial experience for future LArTPC with cold electronics

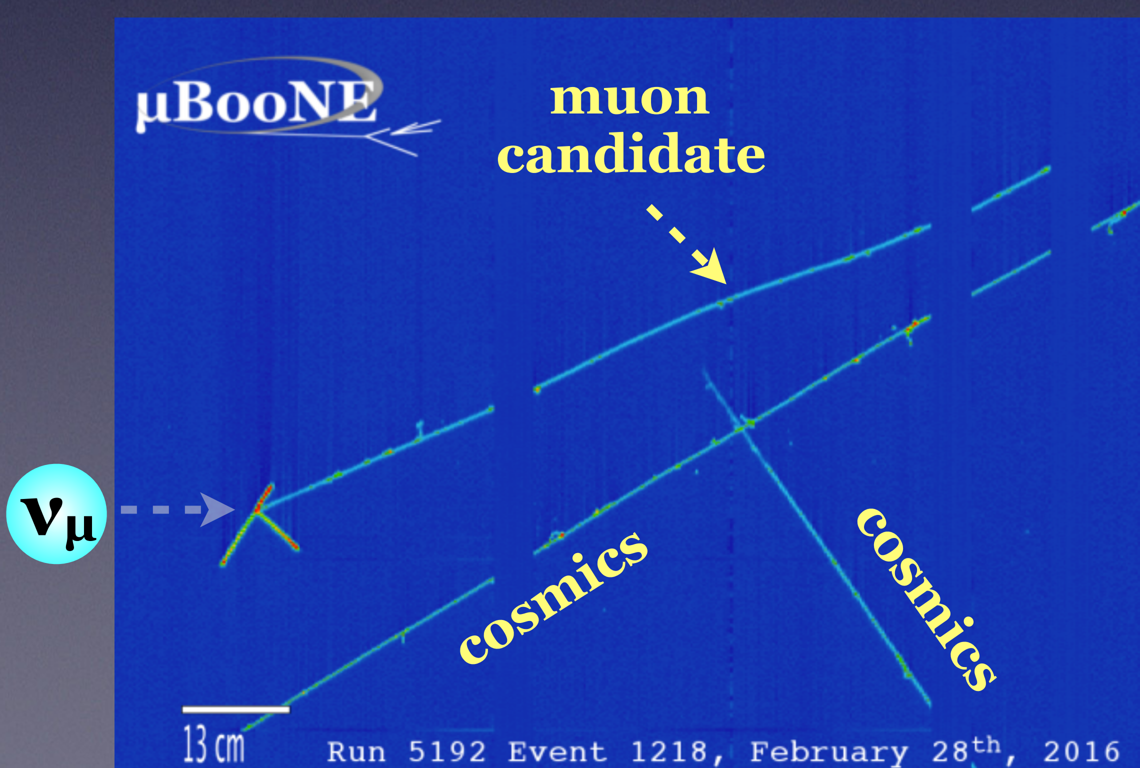
Charged Particle Multiplicity (CPM) Analysis

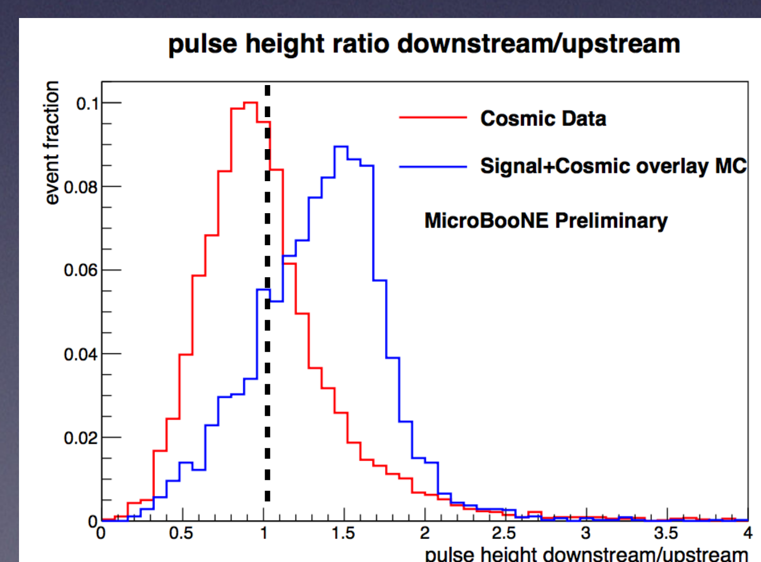
Extension of **CC ν_μ selection**

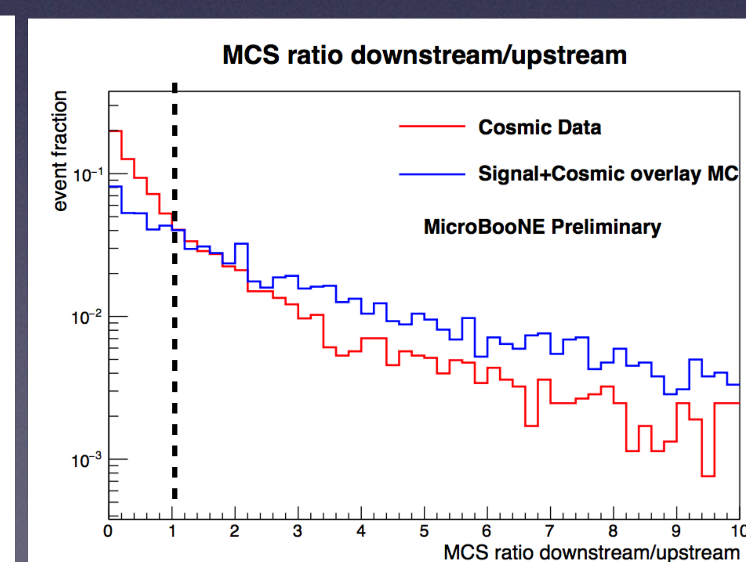
- Count number of reconstructed tracks from interaction vertex
- Using contained ν_μ candidate with a reconstructed "long" muon track
- **Further cosmic rejection cuts**
- UB Public Note 1024 ([link])



CPM Data vs. Simulation

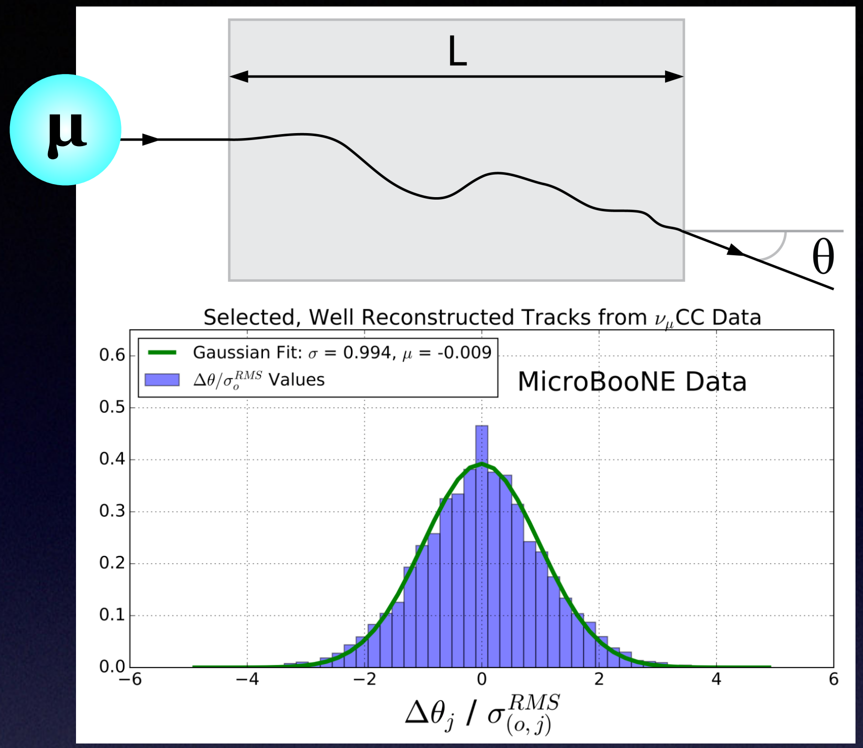






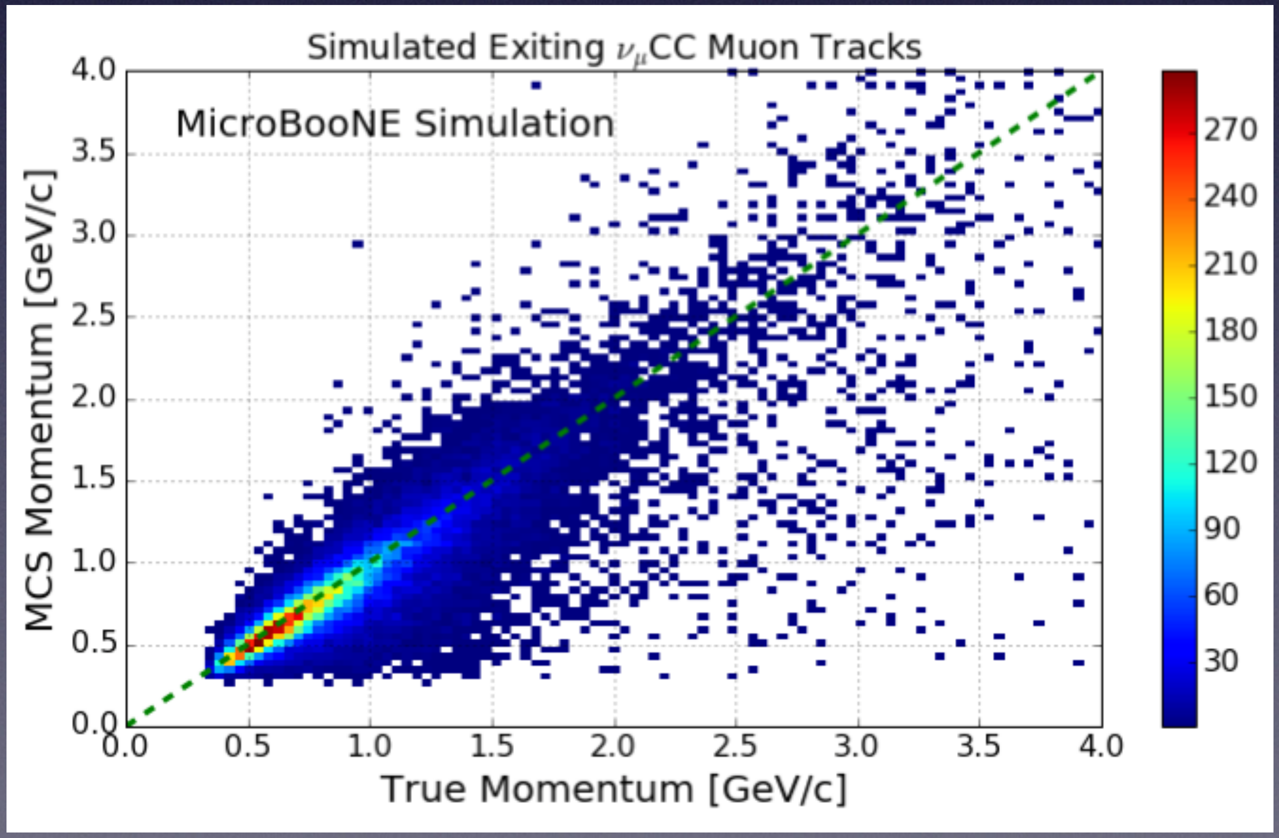
Directionality check on dQ/dX (left) and Multiple Coulomb Scattering angle (right) to reject cosmics

Results on Multiple Coulomb Scattering (MCS)

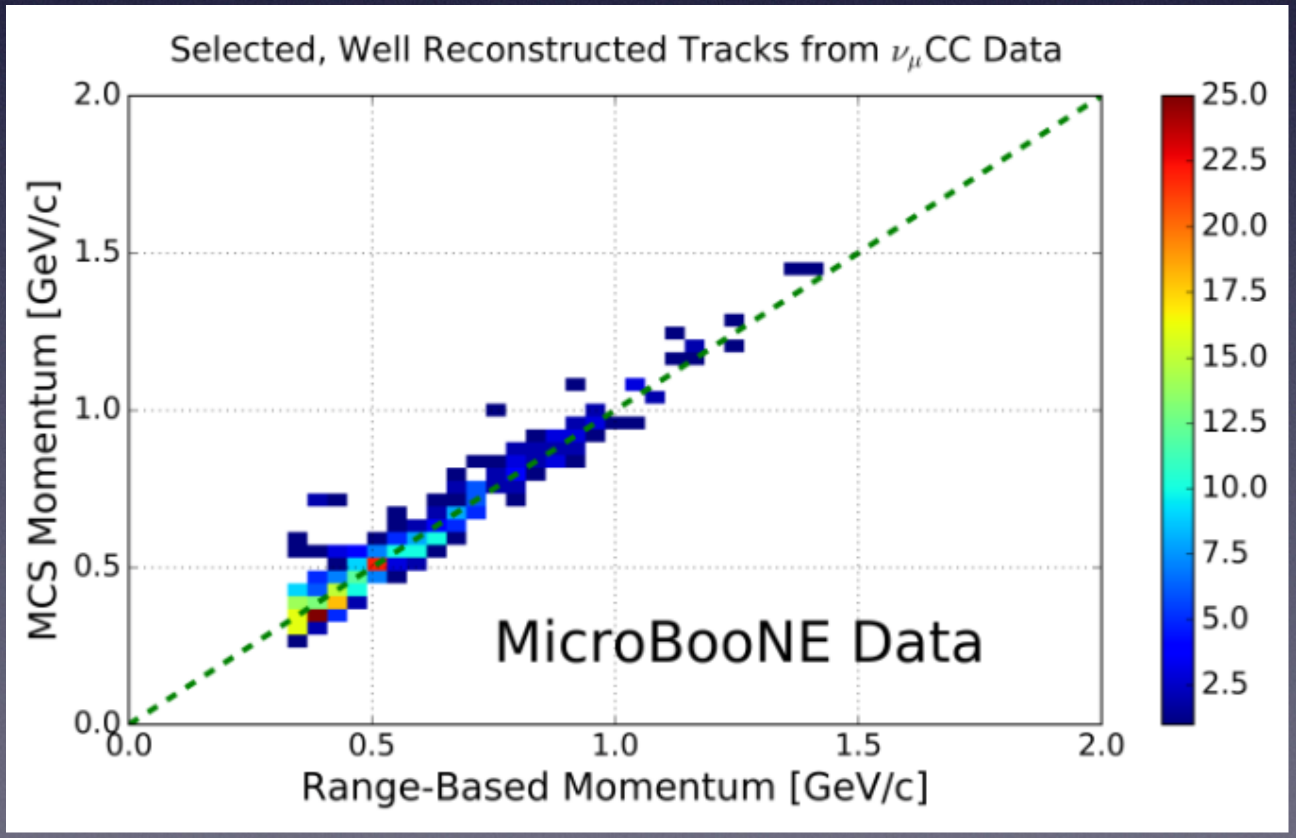


Muon momentum reconstruction

- Contained or exiting **(crucial)**
- Tuned Highland formula for LArTPC, good DATA/MC agreement
- Published: [arXiv: 1703.06187]

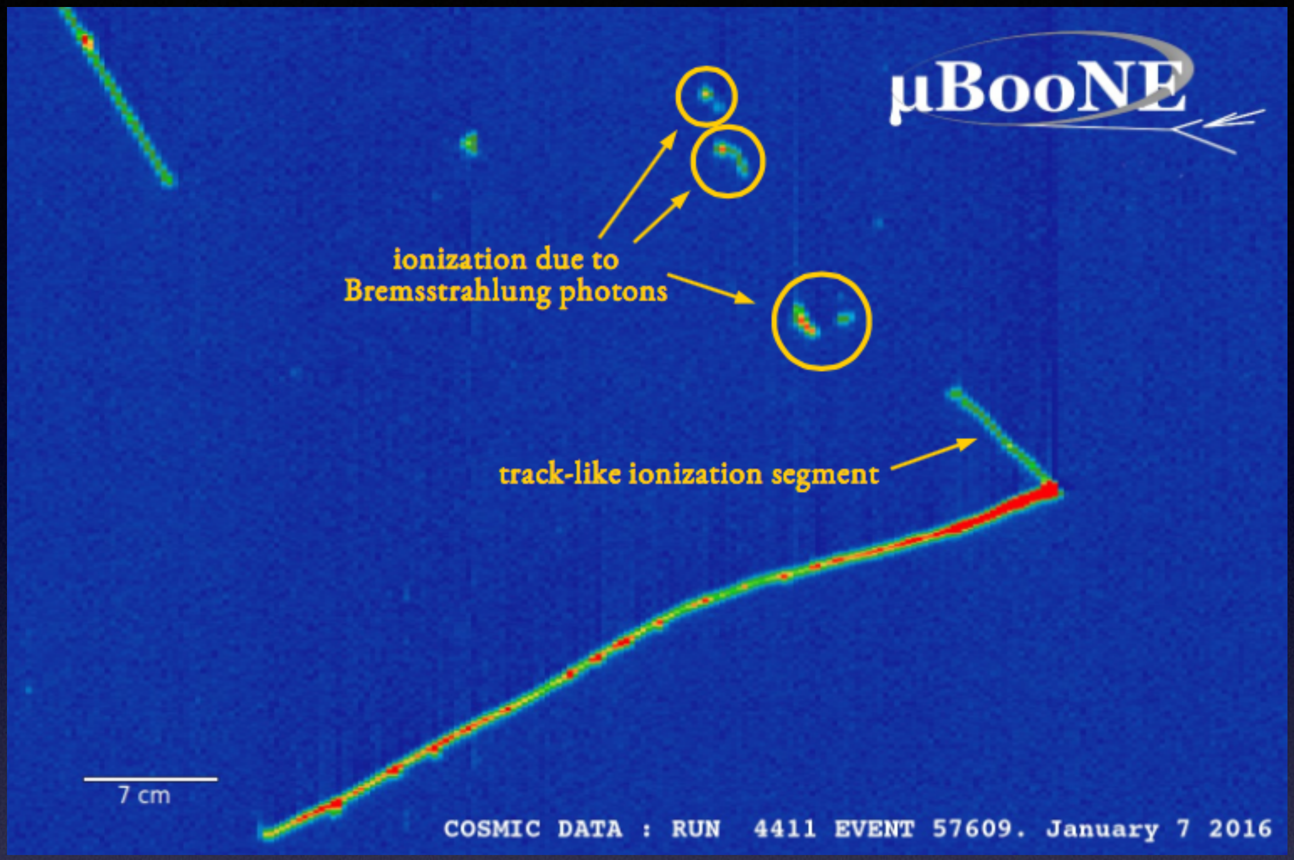


Simulation p_μ Reconstructed (MCS) vs. **Simulated truth**



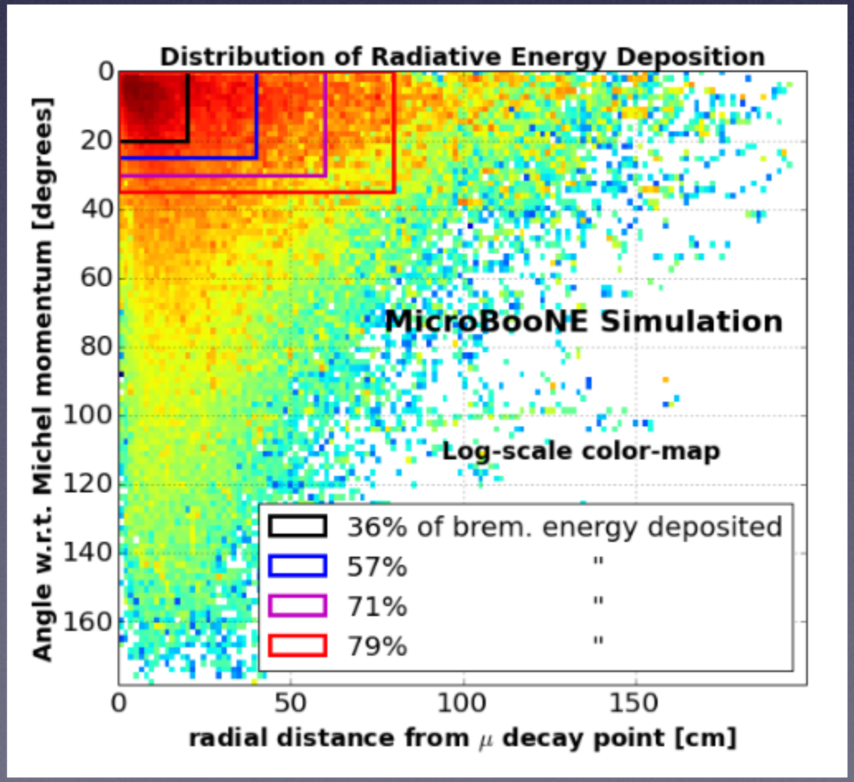
DATA p_μ Reconstructed (MCS) vs. **Range-Based estimation**

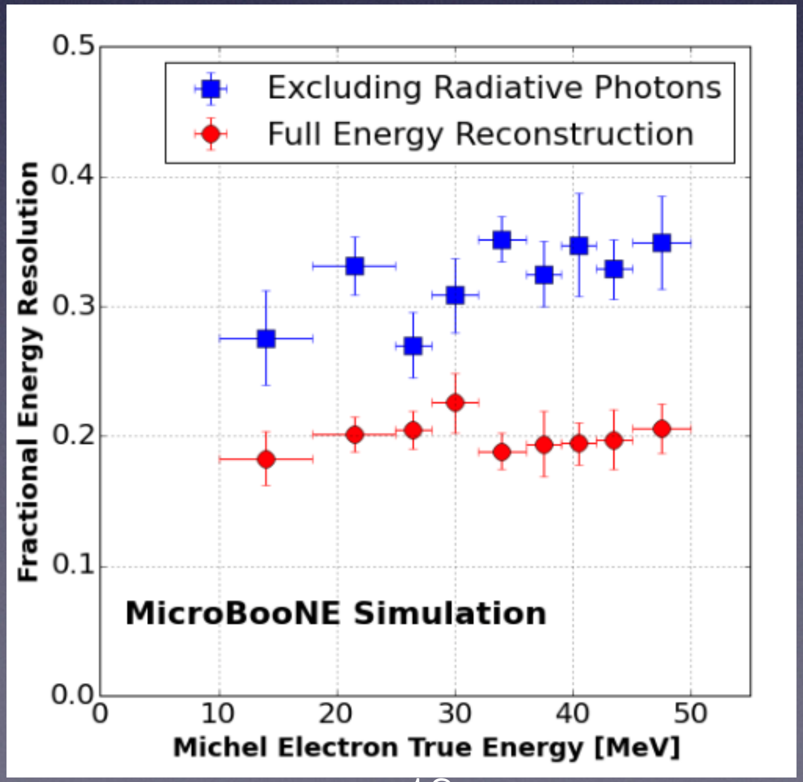
Results on Low Energy e Reconstruction

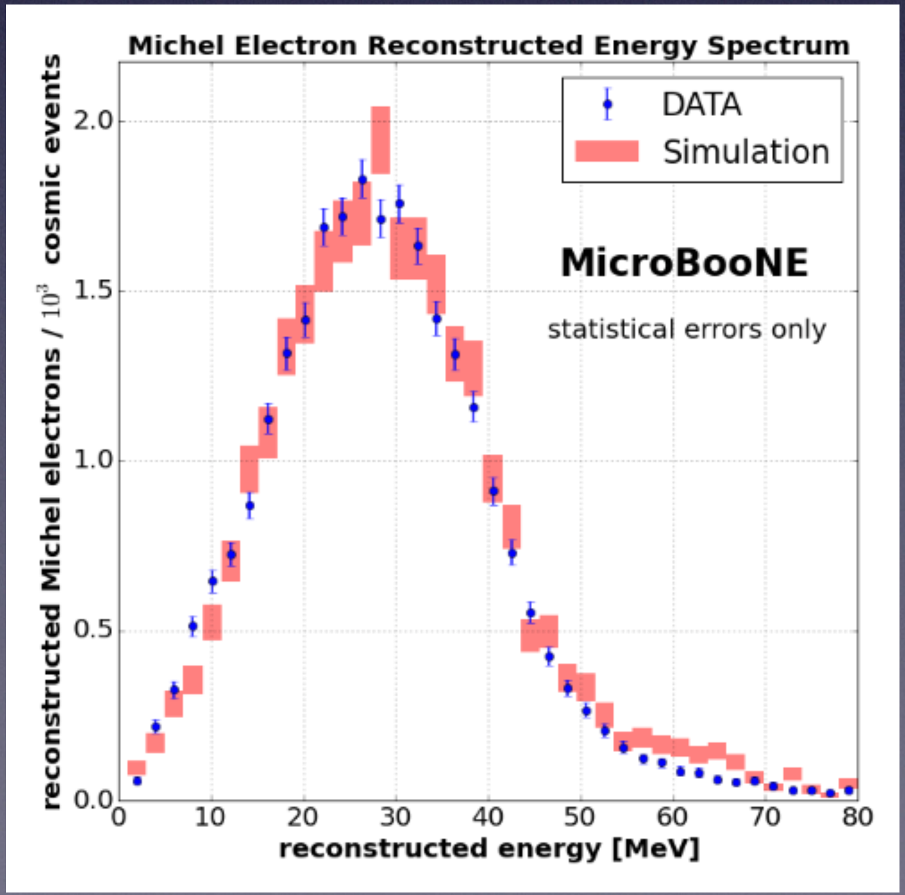


Michel Electron Analysis

- arXiv: 1704.02927
- Automated 2D reconstruction
- **Low energy e$^-$ calibration**
- Challenge of clustering energy depositions by radiative photons



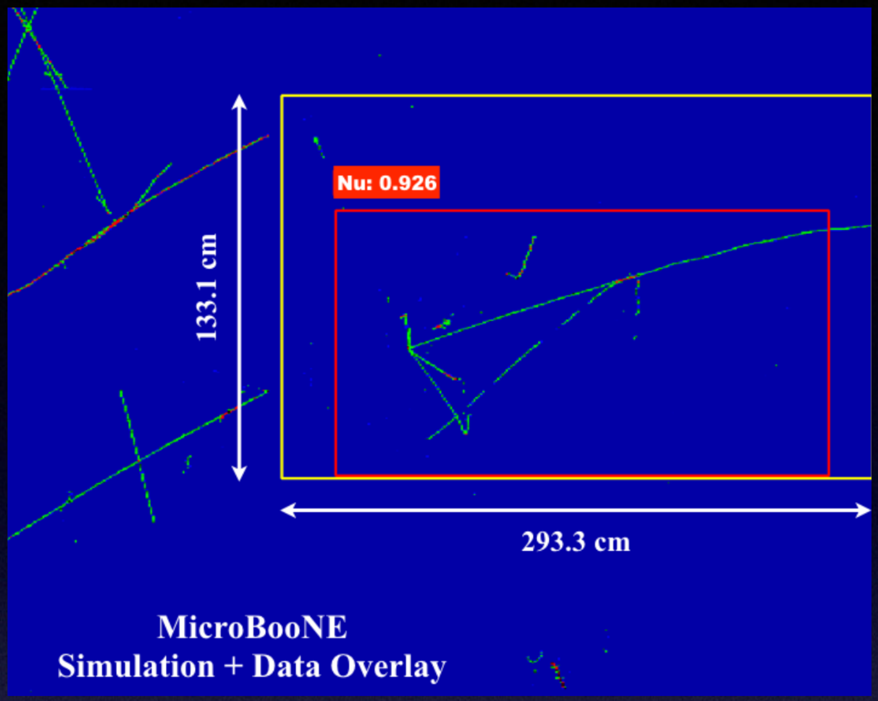




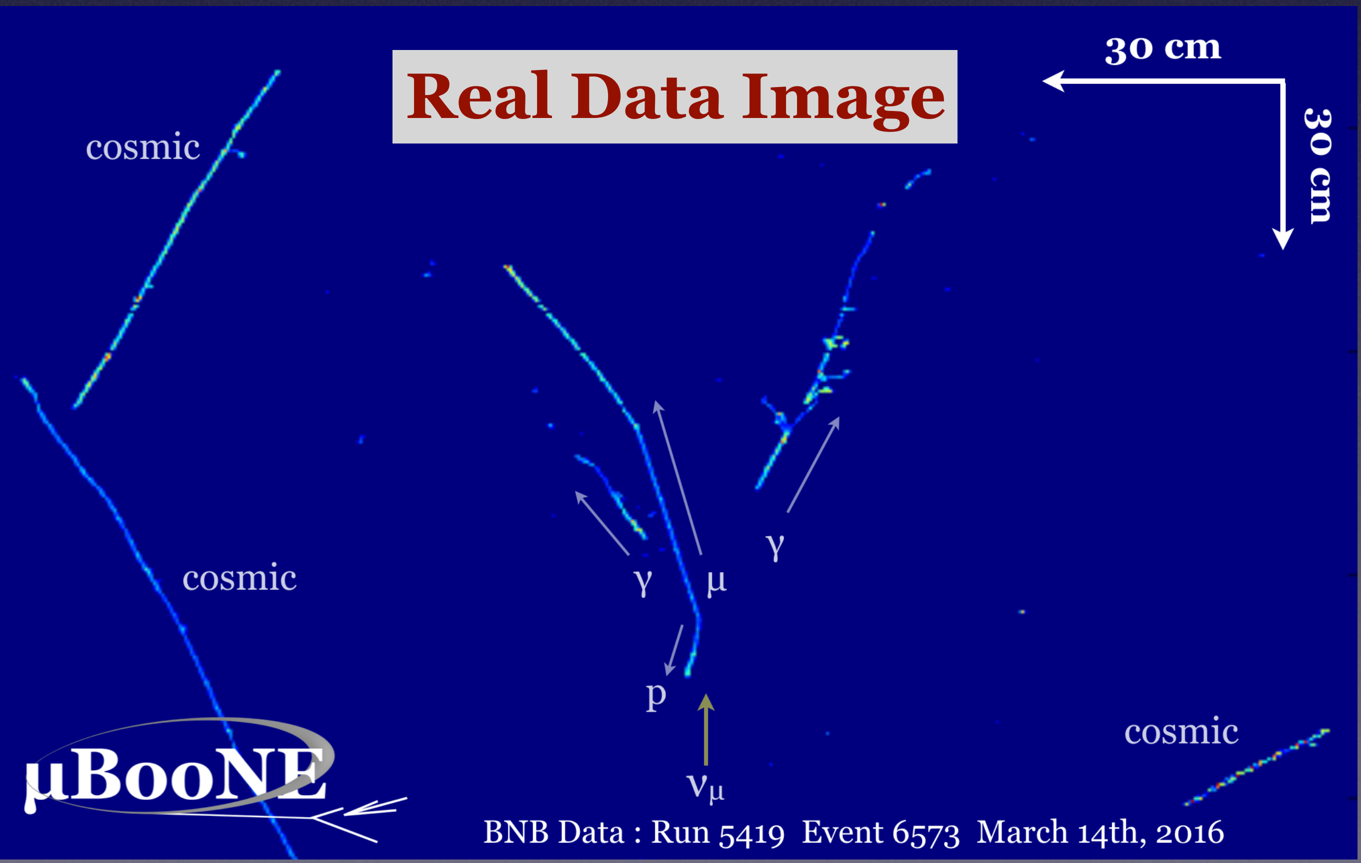
Analysis w/ Convolutional Neural Networks (CNNs)

Machine learning technique

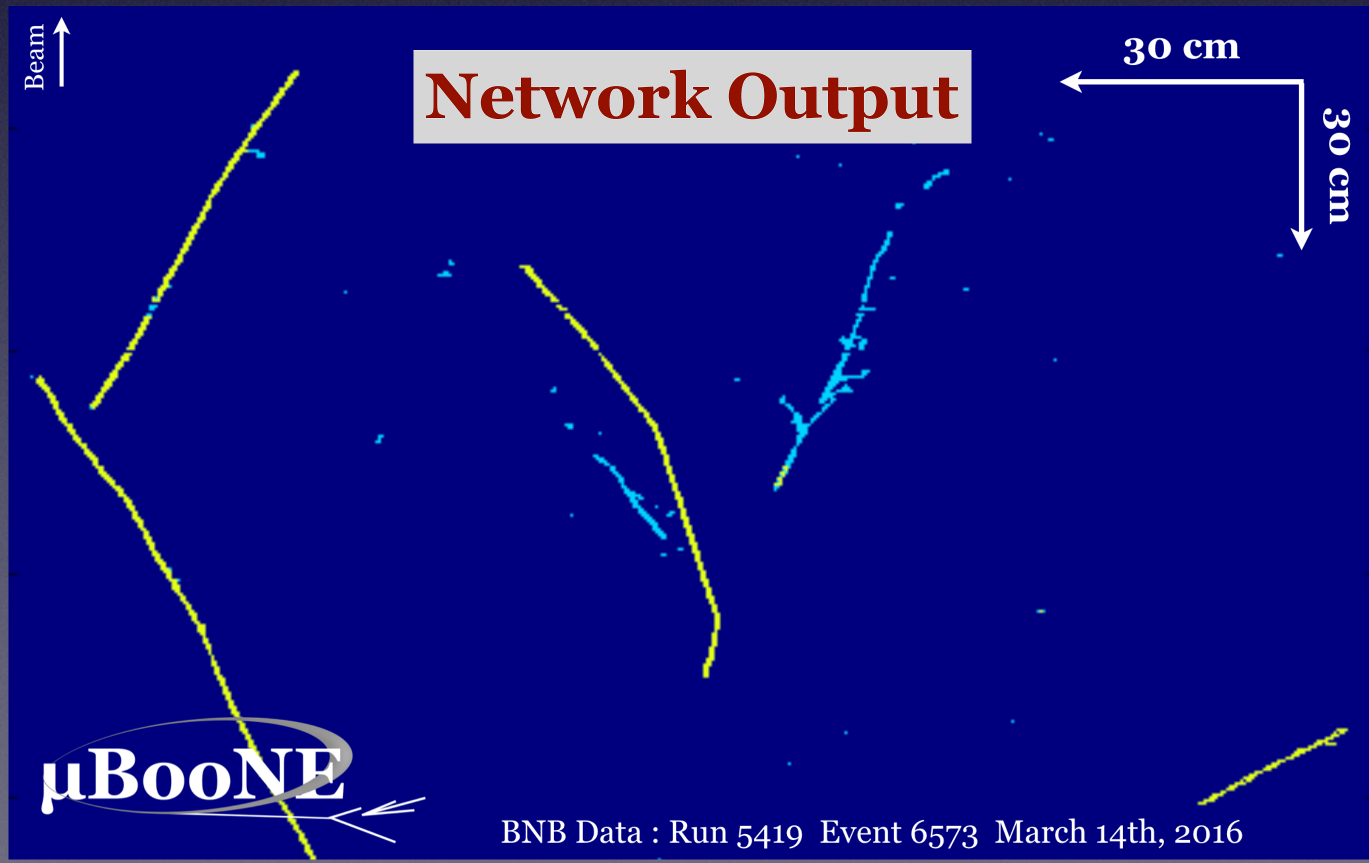
- **Demonstration for LArTPC**
  - Image classification & object detection
  - Particle ID, neutrino vertex localization, etc.
  - JINST 12, P03011
- Using for data reconstruction
  - Pixel-level prediction for shower/track separation



Detection Network



DATA CCπ⁰ Candidate

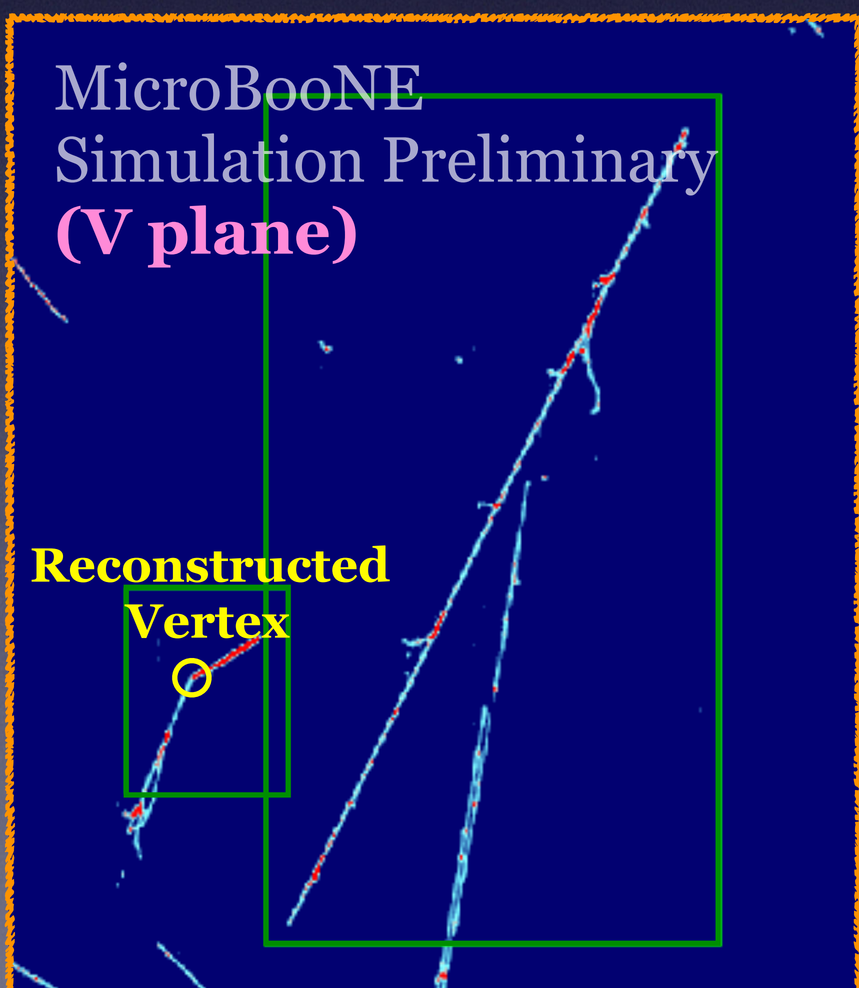


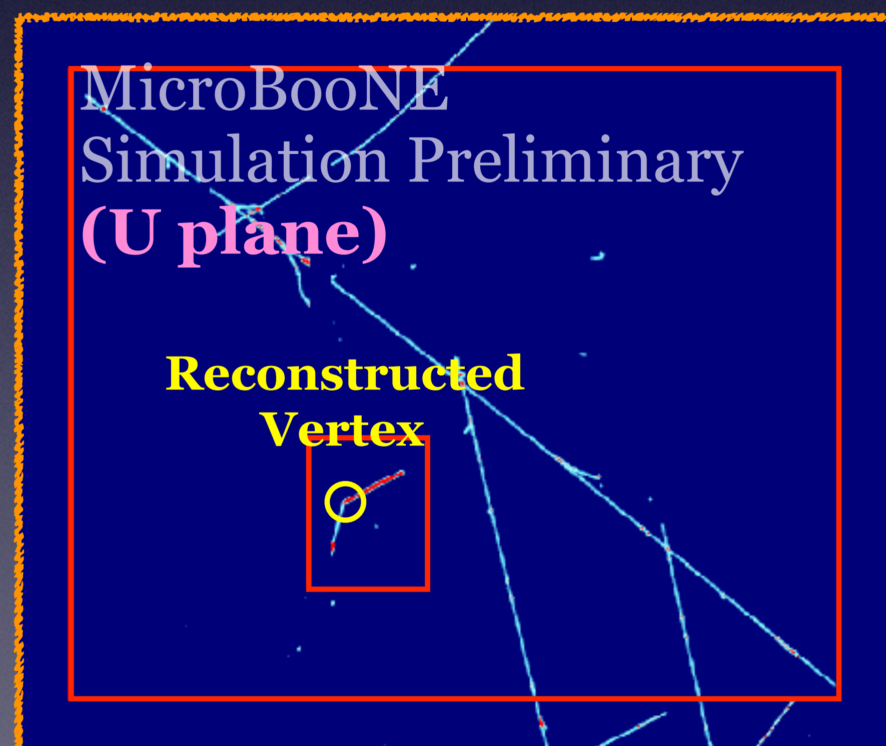
Shower/Track Separation via custom CNN

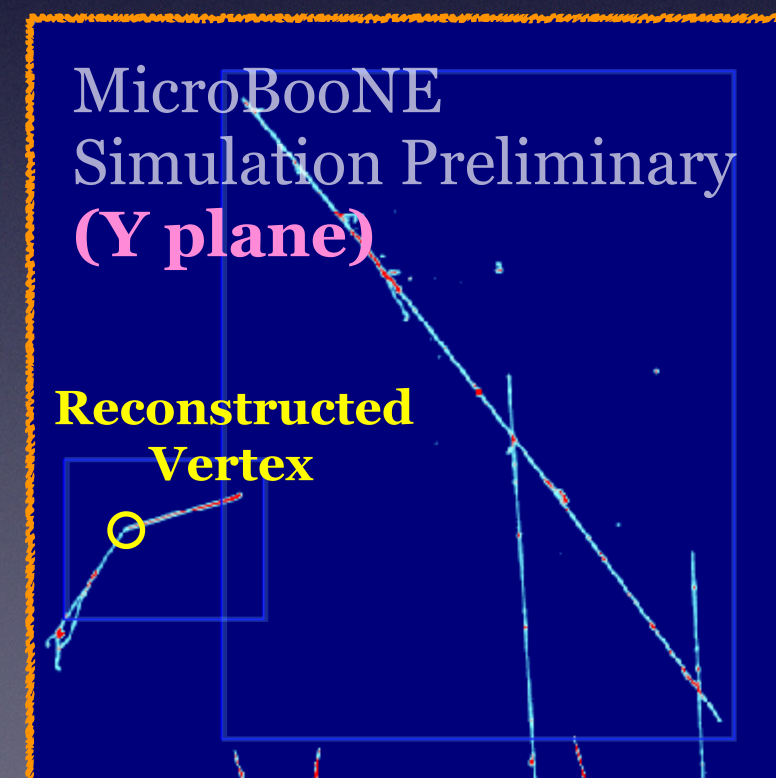
Work Toward Future: ν_e Search

Automated ν_e Search

- Established a fully-automated ν_e reconstruction chain
  - **First look**: a simple **1e-1p topology**
  - First time for LArTPC … tuning for signal/background
- Full chain: cosmic rejection, 3D vertex ID, track/shower separation
  - Using pixel-level shower/track separation by CNN

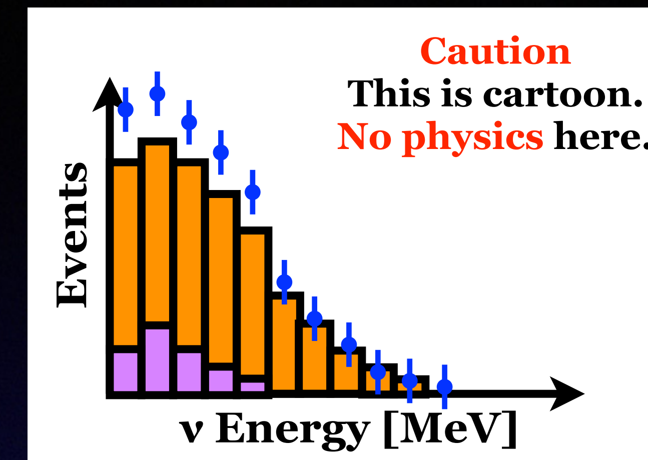






3D reconstructed ν_e vertex (simulation)

Effort Toward Physics Goals

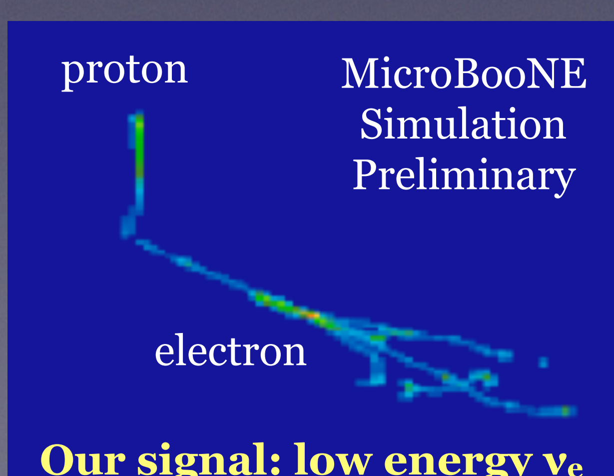


Energy/momentum reconstruction

Particle & event ID

Automated 2D/3D event reconstruction

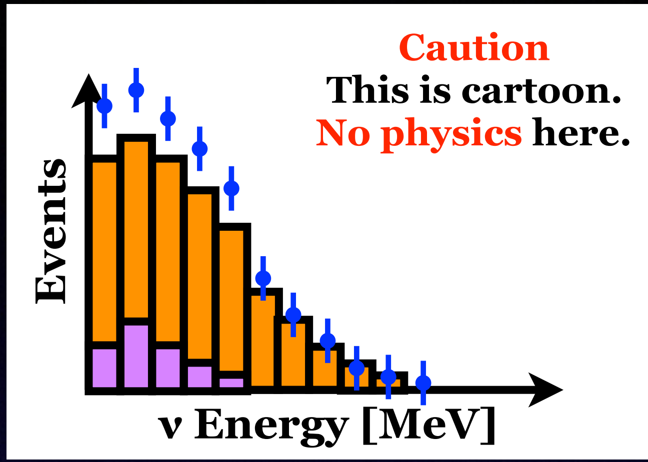
Detector response calibration



slide design, courtesy of A. Schukraft

Effort Toward Physics Goals (Today)

- **5 papers** (published, link)
- **15 public notes** (toward publication, link)



Detector response calibration

Automated 2D/3D event reconstruction

Particle & event ID

Energy/momentum reconstruction

★ *Design and Construction of the **MicroBooNE Detector***
JINST 12, P02017 (2017)

★ ***Noise characterization** and filtering in the MicroBooNE Liquid Argon TPC (arXiv:1705.07341)*

★ ***The Pandora** multi-algorithm approach to **automated pattern recognition** of cosmic-ray muon and neutrino events in the MicroBooNE detectorer*
coming soon

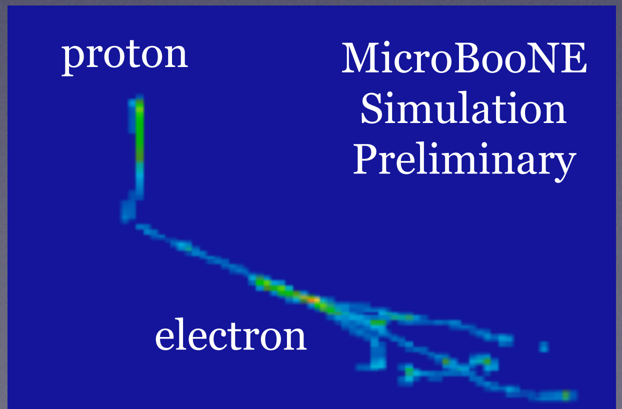
★ ***Convolutional Neural Networks** Applied to Neutrino Events in Liquid Argon Time Projection Chamber*
JINST 12, P03011 (2017)

★ *Measurement of **cosmic-ray reconstruction efficiencies** in MicroBooNE using a small external cosmic-ray counter*
coming soon

See Roberto S's talk on Friday!

★ *Determination of **muon momentum** in the MicroBooNE LArTPC using an improved model of **multiple Coulomb scattering***
(arXiv:1703.06187)

★ ***Michel Electron** Reconstruction Using Cosmic-Ray Data from the MicroBooNE LArTPC*
(arXiv:1704.02927)



Our signal: low energy ν_e

slide design, courtesy of A. Schukraft

μBooNE

Latest Results
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Outline
- MicroBooNE: short baseline experiment
- Current status and latest results
- Wrap-up

… Wrapping Up …

MicroBooNE has been stably running

- Since 2015, collected 5.5 E20 POT BNB data

Publications toward final physics results

- **Physics**
  - Michel electron, MCS, CPM analysis (public note)
- **Technical**
  - Reconstruction: CNN, Pandora (public note)
  - Detector design, Noise characterization
- Important **results not mentioned in this talk**
  - NC proton track identification (public note)
  - Space charge effect (public note)

Future prospects

- More toward detector calibration & cosmic rejection
- CC ν_μ analysis & ν_e signal search

μBooNE

MicroBooNE Collaboration

Thank you
for
your attention!

Any Questions 

Run 3493 Event 41075, October 23rd, 2015

75 cm

Back Up Slides
That Hopefully Back Me Up

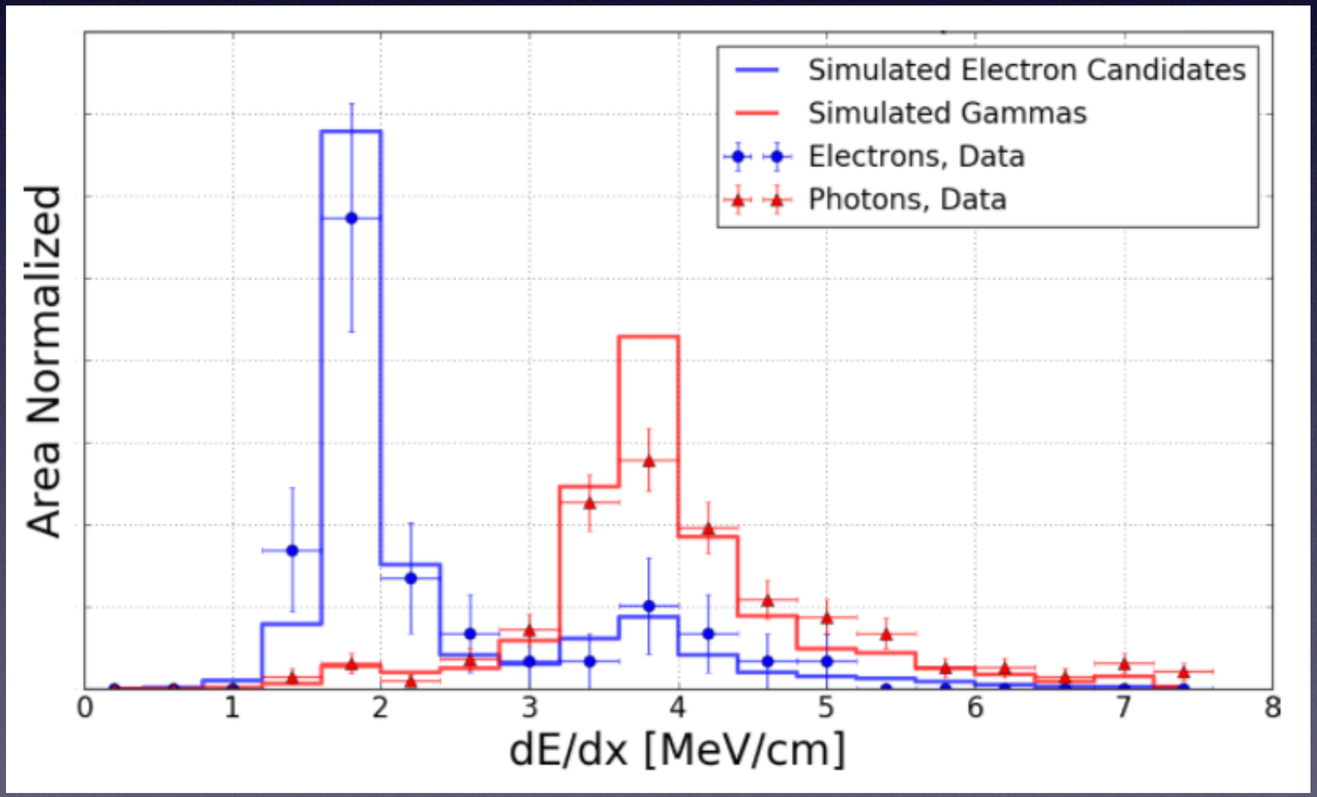
Misc.

A Probe for EM Showers in MicroBooNE

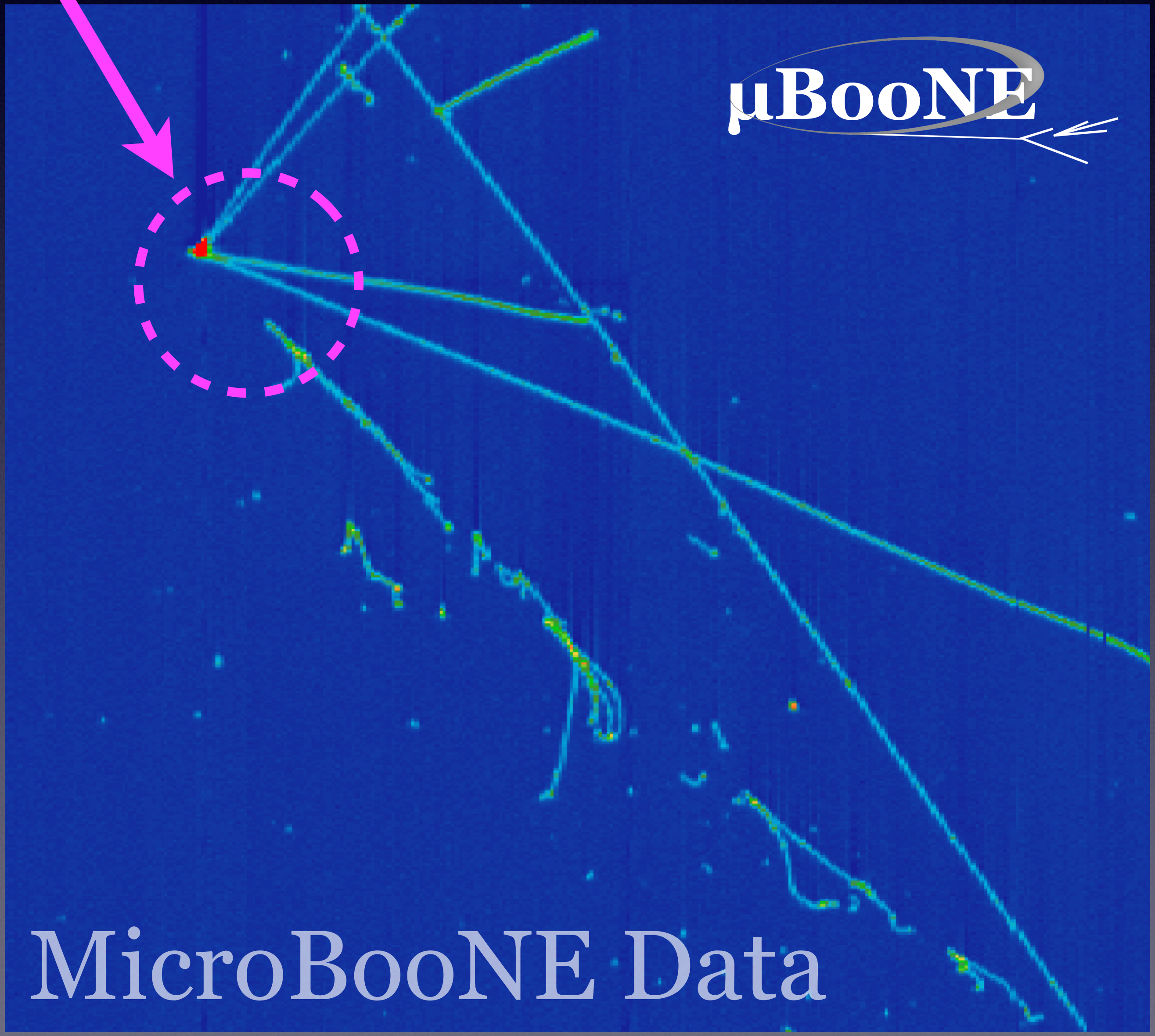
Two handles for e^-/γ separation in LArTPC

1. **"Gap"** from the vertex to γ shower start
2. dE/dX @ shower start
   - γ makes twice MIP dE/dX

arXiv:1610.04102

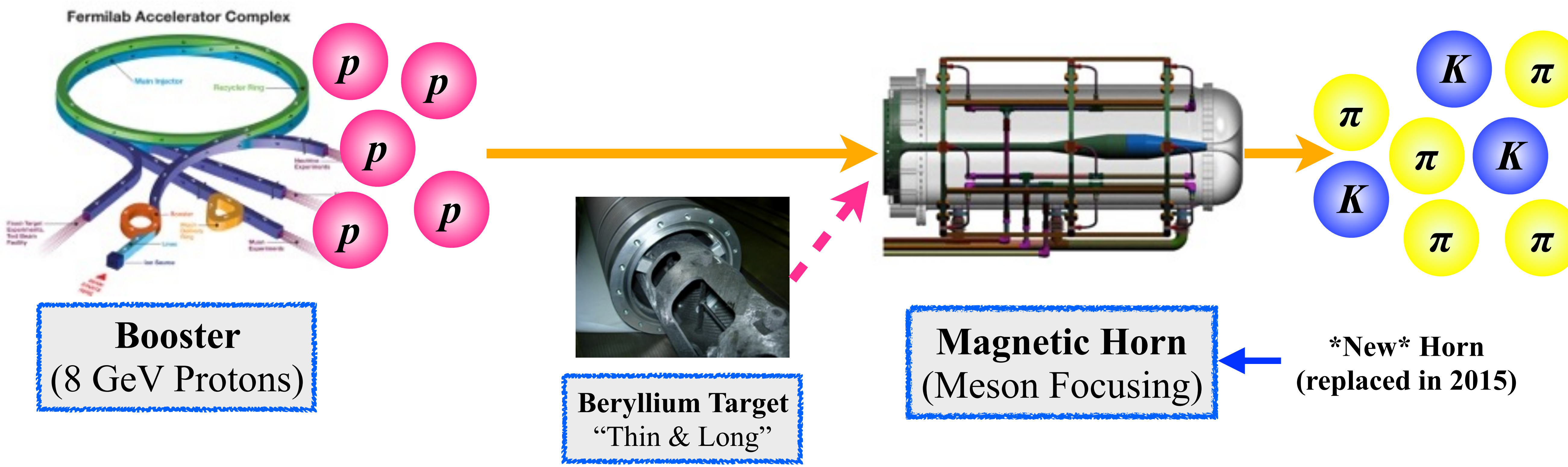


dE/dX (ArgoNeuT)
e^- vs. **γ** discrimination

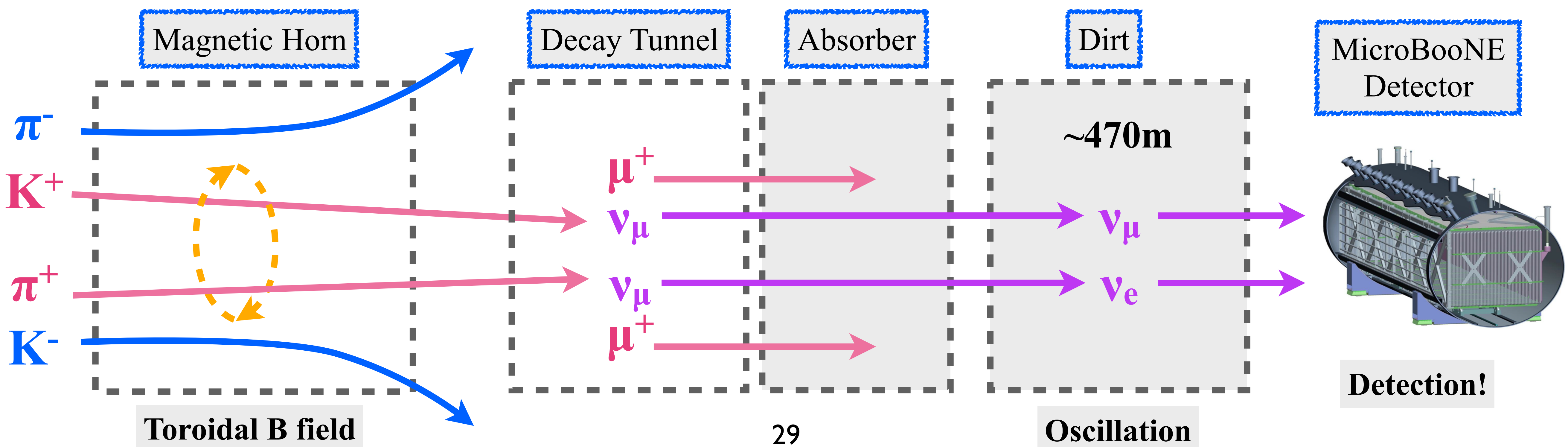


BNB: Neutrino Source

- 8 GeV protons from Booster hits Beryllium target to produce mesons



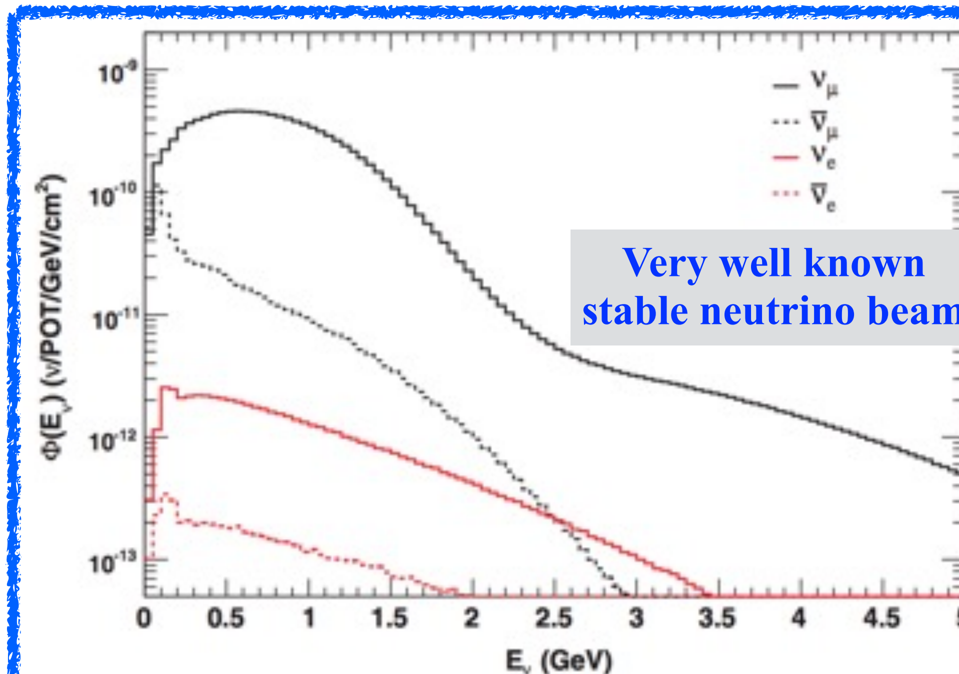
- Horn focuses positive (negative) mesons to produce neutrinos (anti-nu)



BNB: Providing Neutrinos Over a Decade

MicroBooNE @ FNAL

PRD 79, 072002 (2009)



Very well known stable neutrino beam

Horn: Neutrino Mode

Event Rate Break Down

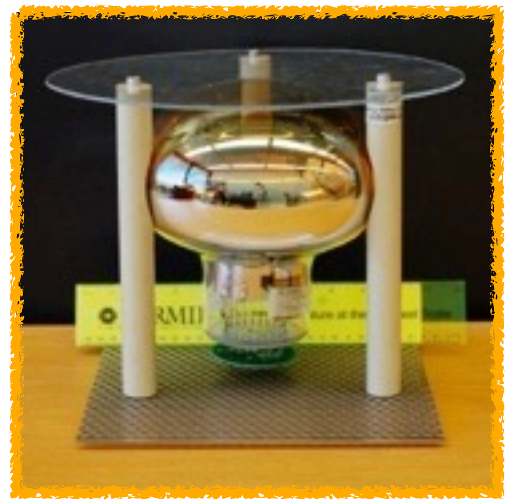
(flux & xs)

- $\nu_\mu \simeq 93.6\%$
- $\bar{\nu}_\mu \simeq 5.86\ \%$
- $\nu_e \simeq 0.5\ \%$
- $\bar{\nu}_e \simeq 0.05\ \%$

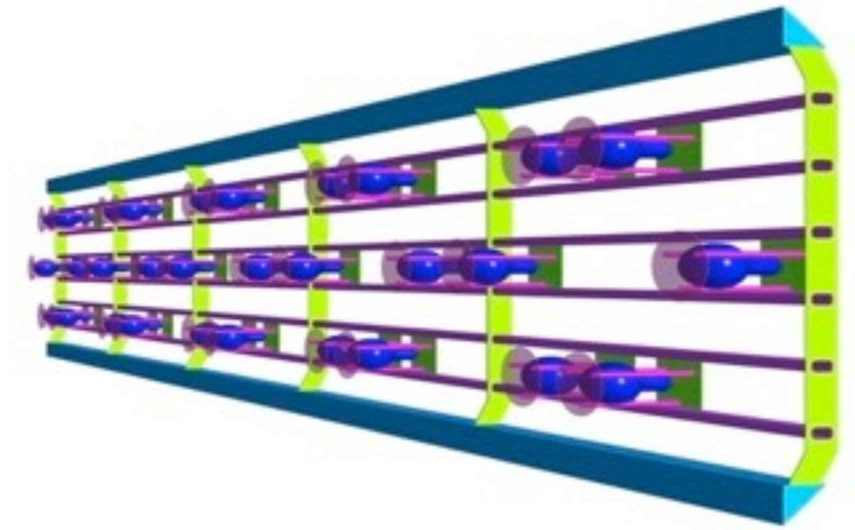
... high purity ν_μ beam ...

Optical Detector

- **What is it? What for?**
  - 32 8” PMTs
  - Crucial roles
    - **Getting trigger**
    - **Reconstructing YZ**
    - ✓ **Cosmic background rejection**



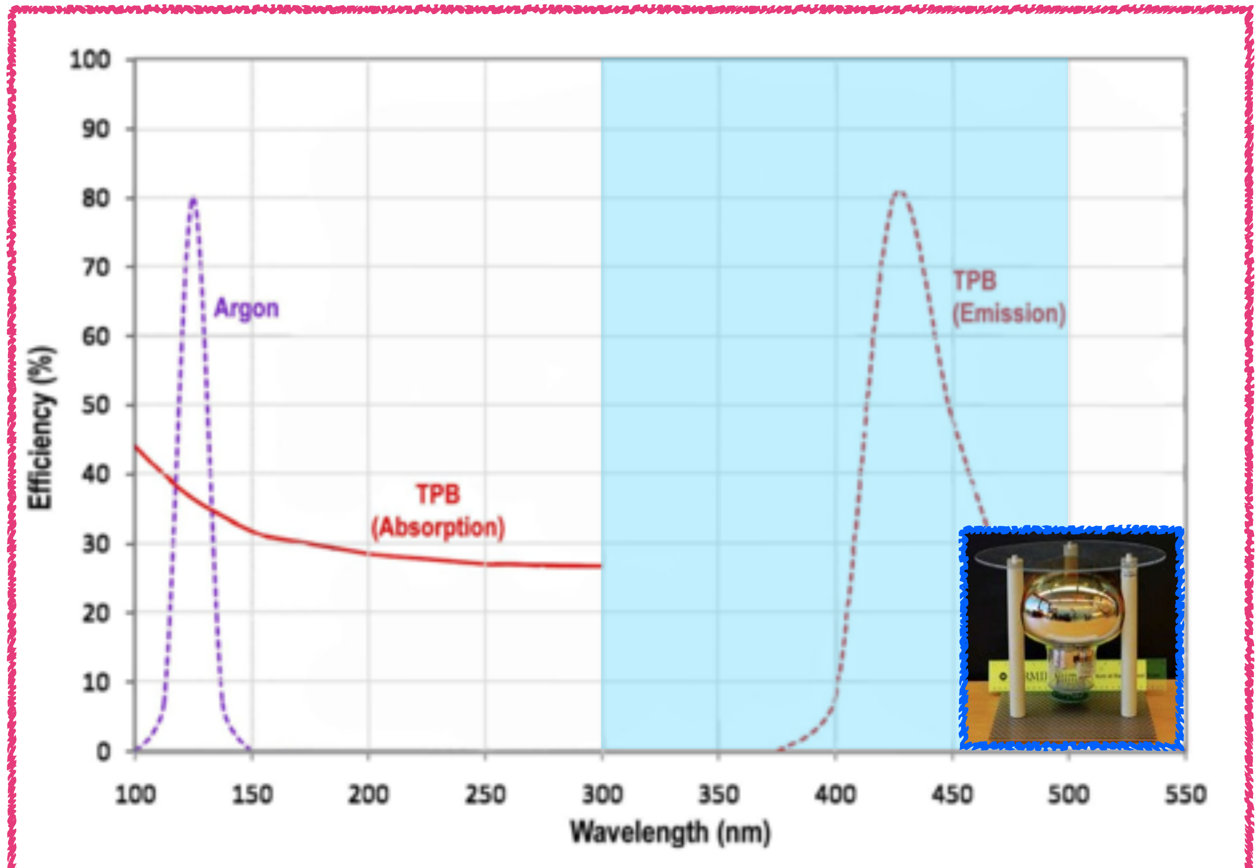
MicroBooNE PMT



Array of 32 PMTs

Crucial for MicroBooNE
because of
high cosmic ray rate (~5kHz) @ surface!

- **LAr optical properties**
  - No detail here... but LOTS of physics!
    - Read arxiv 1306.4605 for instance
  - Produced within **6 ns** of interaction
  - High light yield ≃ 6000 photons / MeV
  - **“Transparent” to its own light**
    - No re-scintillation (does Rayleigh scatter)
    - Wavelength shift by **TPB**



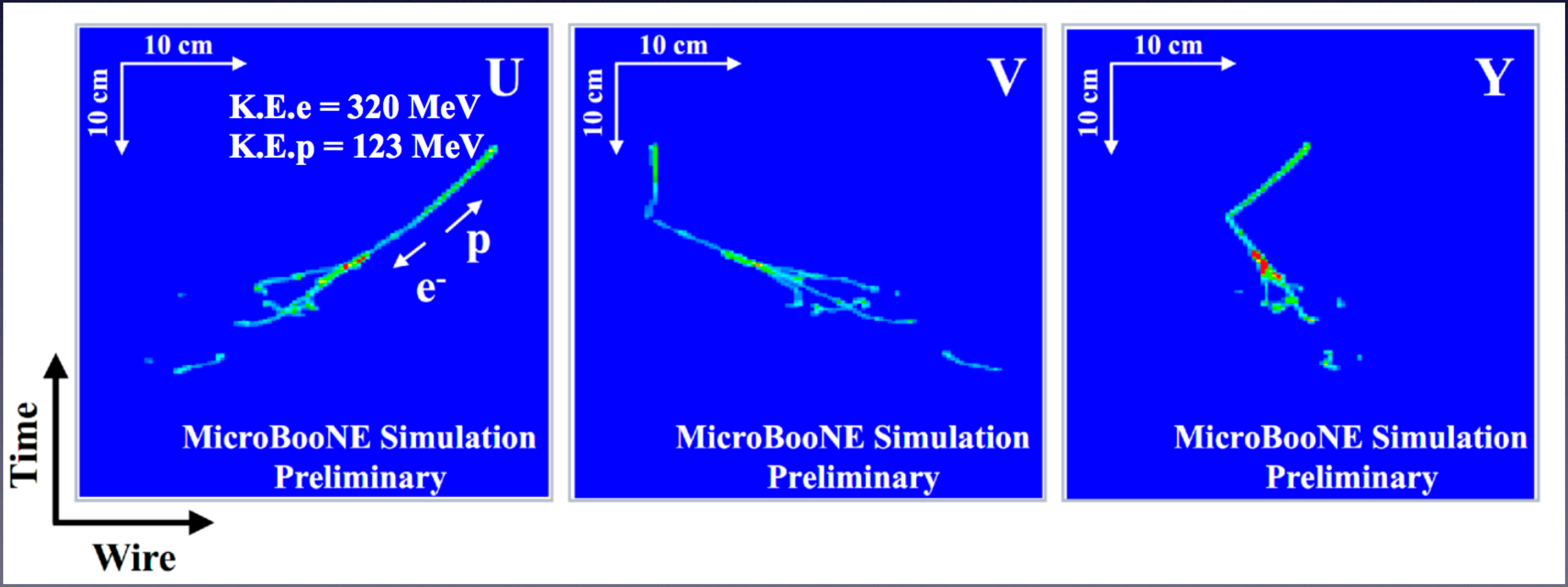
TPB shifts wavelength from 128 nm to 430 nm, appropriate for PMTs

LEE Analysis Chain

Toward Future: ν_e Search

Automated ν_e Search

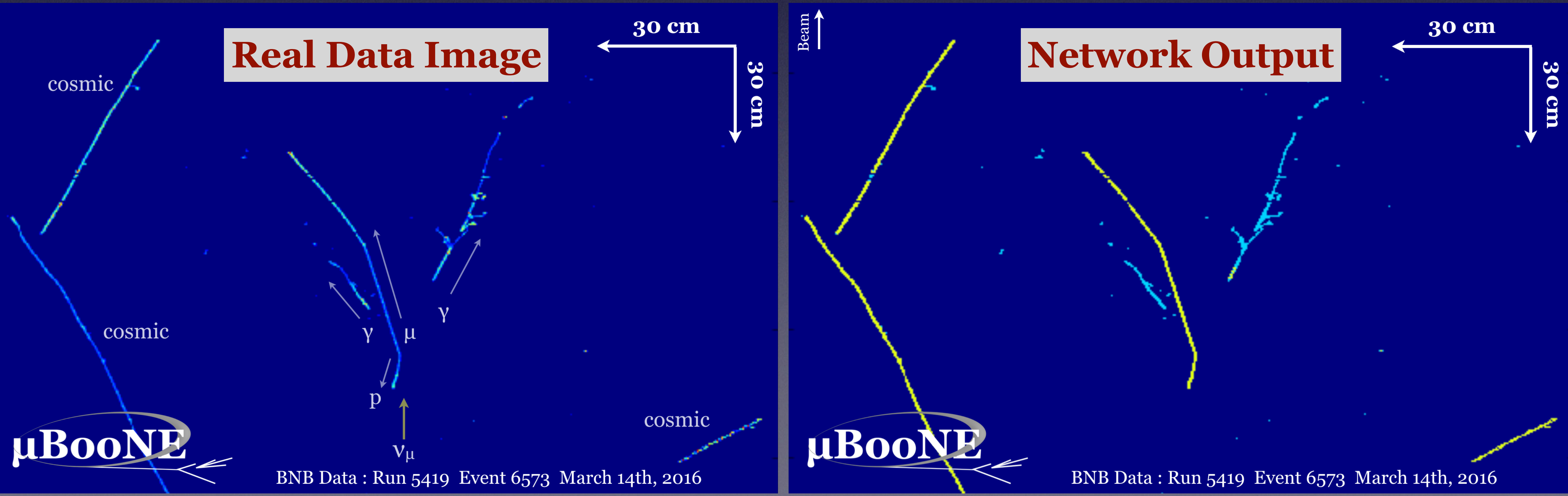
- Collaborative effort, first time full automation!
- **First look**: a simple **1e-1p topology**
  - Multiple approaches, this is just one type



Toward Future: ν_e Search

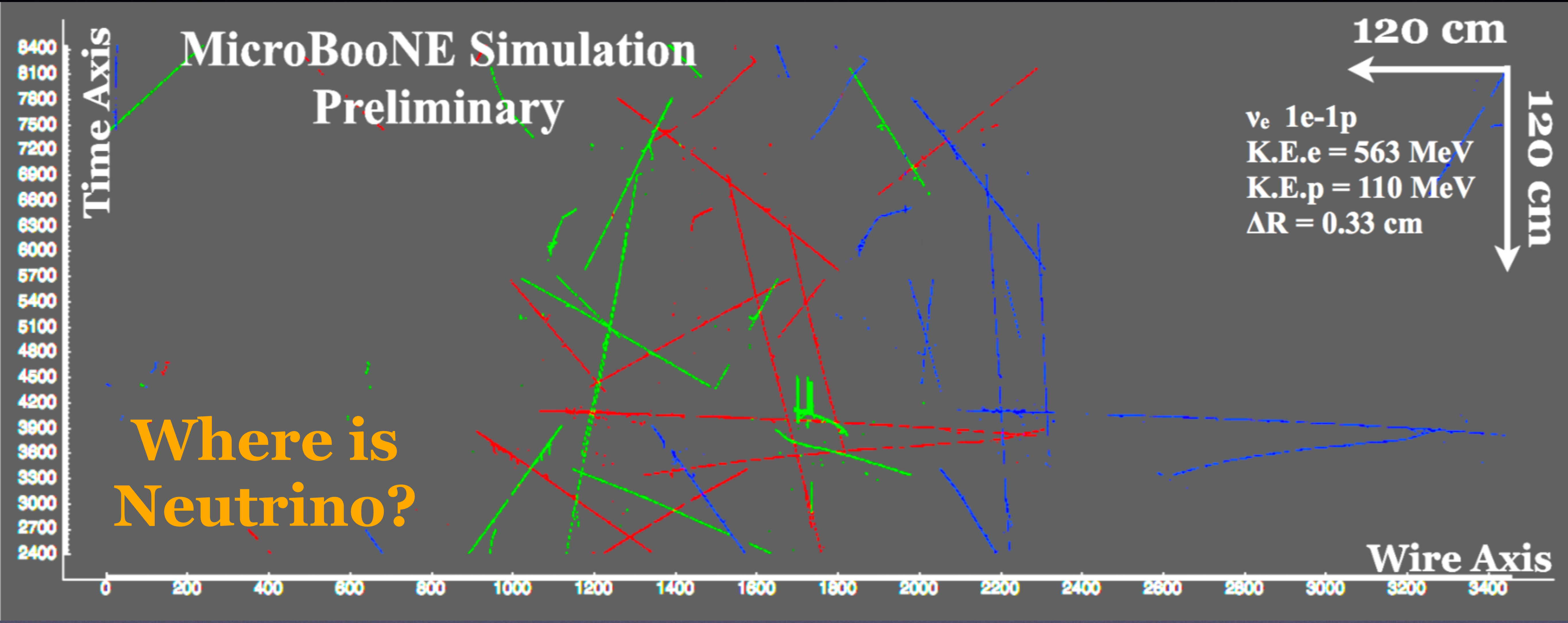
Automated ν_e Search

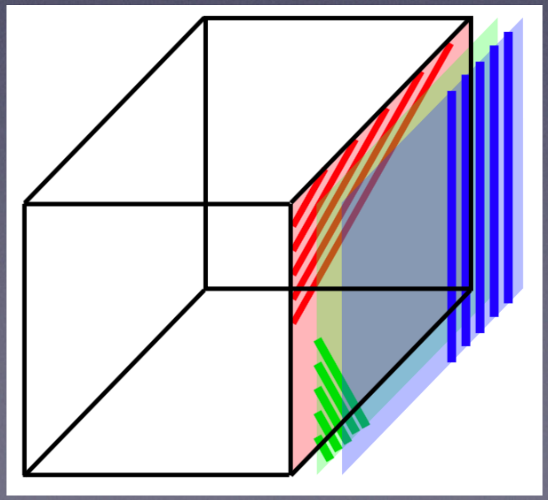
- Collaborative effort, first time full automation!
- **First look**: a simple **1e-1p topology**
  - Multiple approaches, this is just one type
- Mitigate a difficulty of identifying shower cluster using convolutional neural networks



Toward Future: ν_e Search

Automated ν_e Search

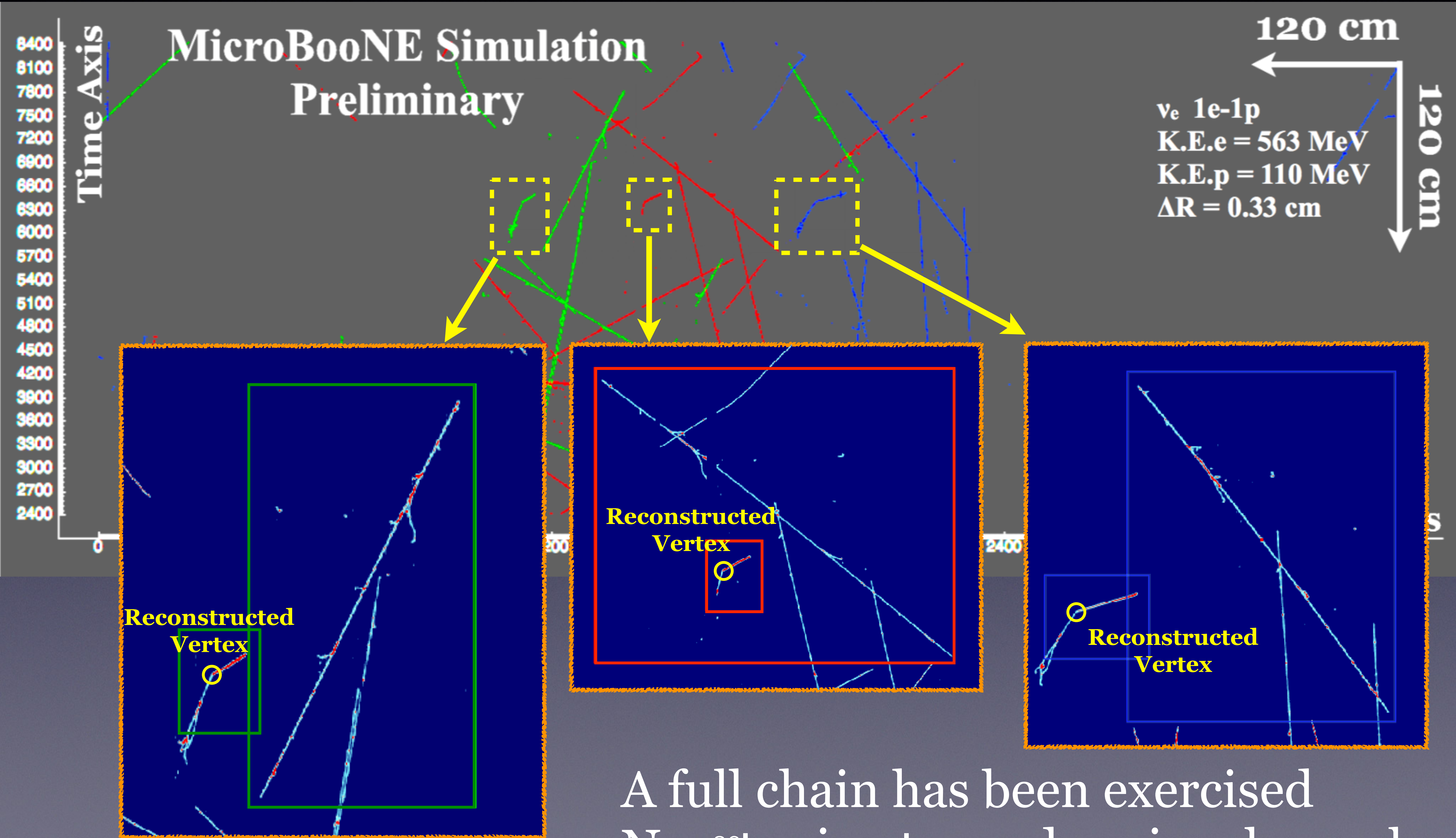




- Viewing all 3 planes together
  - RGB … 1 color per plane
  - 3D particle track shows up on all planes
  - Time on Y-axis, wires (beam) on X-axis

On-Going Work: ν_e Search

Automated ν_e Search



A full chain has been exercised
Now tuning toward ν_e signal search

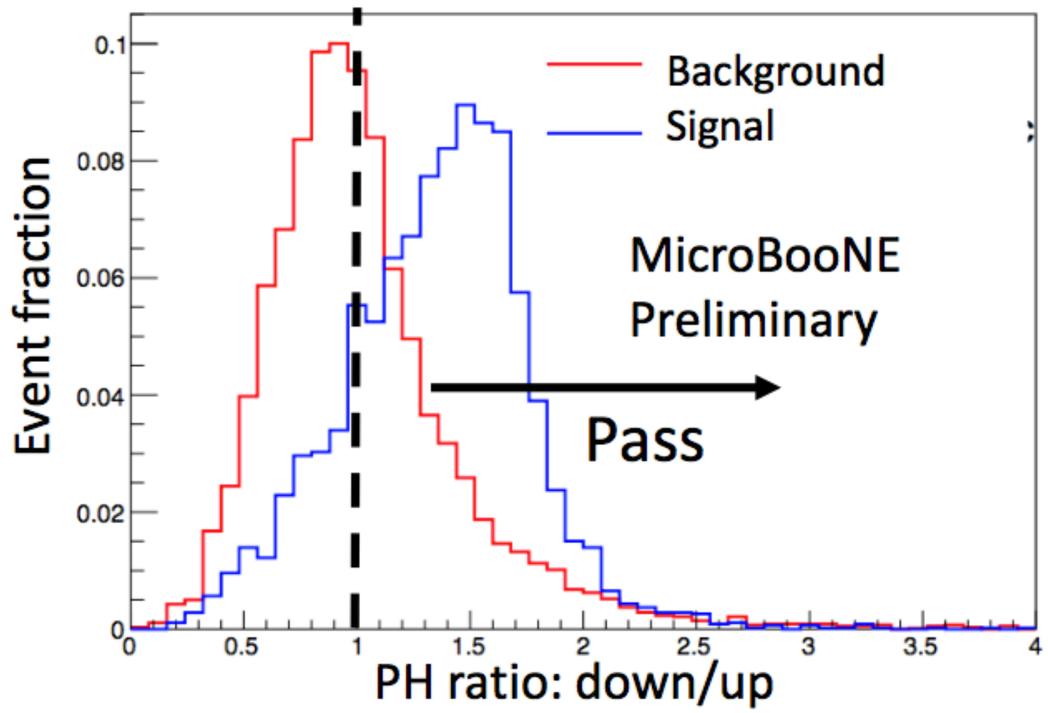
CPM Analysis Details

Slide courtesy of **Aleena F.** presented at [Fermilab User's Meeting]

PH and MCS Test

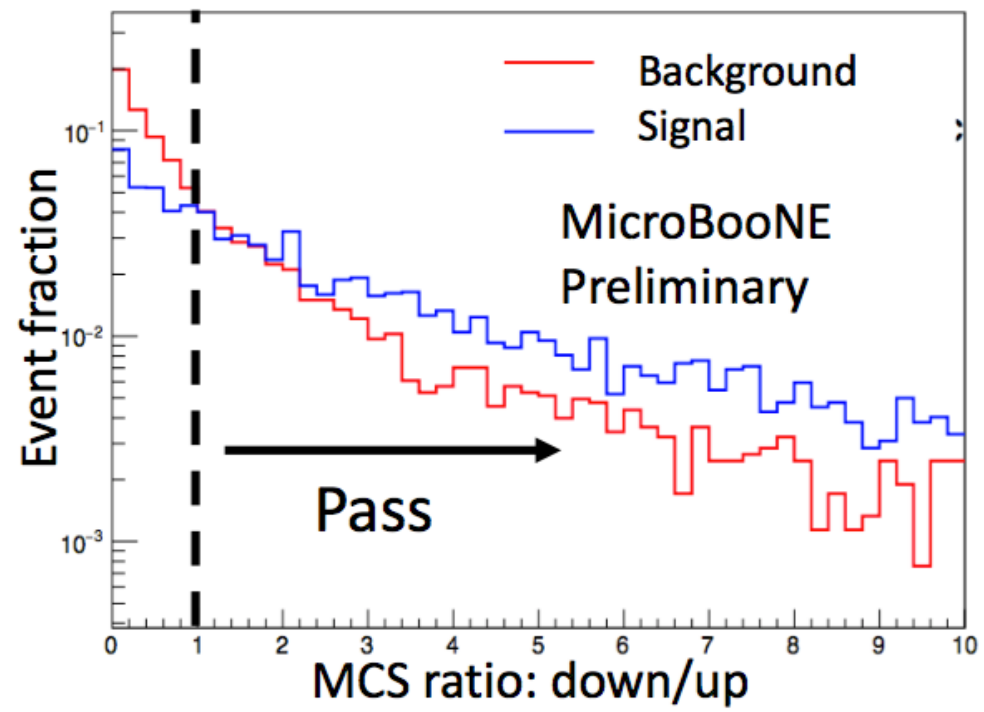
PH Test

Rate of energy loss increases along the track from upstream to downstream end



MCS Test

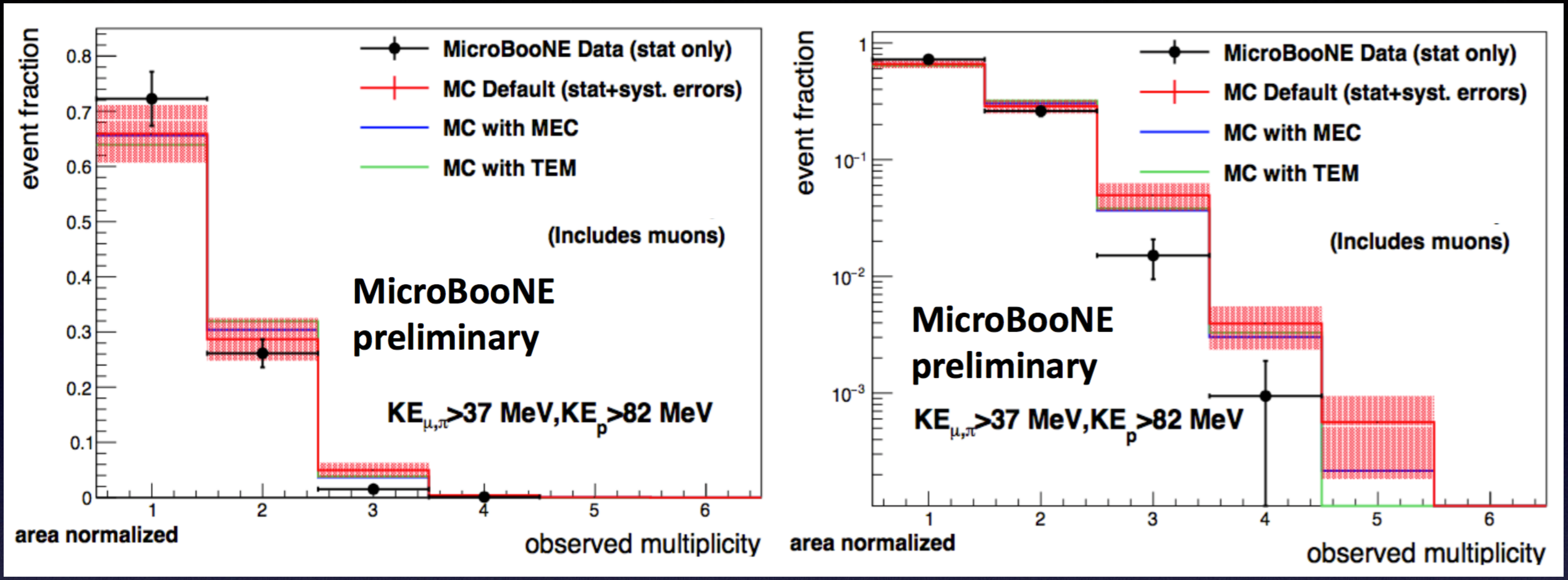
Scattering is more pronounced along the downstream end of the track as the momentum decreases.



Sub samples	On-beam Data		Off-beam Data		BNB+Cosmic Default MC	
PH, MCS	events	acceptance rates	events	acceptance rates	events	acceptance rates
pass, pass	847	(44%)	1263	(24%)	2629	(62%)
pass, fail	367	(19%)	1087	(21%)	737	(18%)
fail, pass	321	(17%)	1141	(22%)	440	(10%)
fail, fail	387	(20%)	1776	(34%)	403	(10%)

Cosmic rays travel forward and backward with roughly equal prob.

CPM Analysis Uncertainties

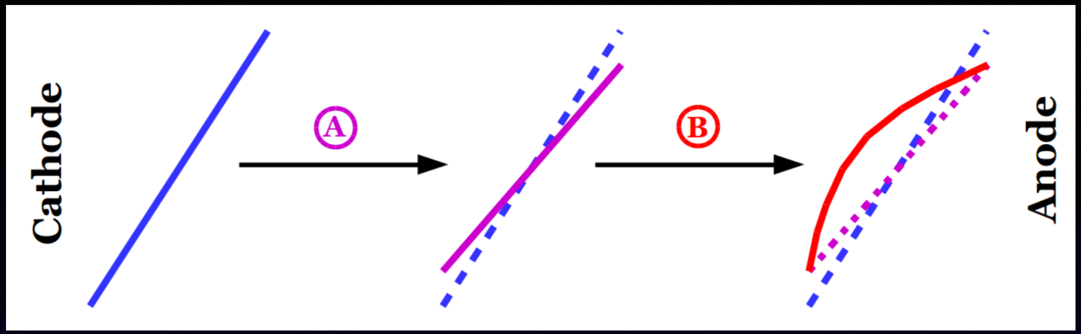


Uncertainty Sources	Uncertainty Estimates mult=1	mult=2	mult=3	mult=4	mult=5
Data statistics	7%	10%	38%	100%	–
MC statistics	3%	4%	7%	21%	50%
Short track efficiency	7%	11%	25%	33%	44%
Long track efficiency	1%	2%	4%	7%	9%
Fixed model parameter systematics	2%	2%	0%	0%	0%
Flux shape systematics	0%	0.4%	0.2%	0.5%	0.8%
Electron lifetime systematics	0.5%	0.1%	6%	5%	5%

Largest non-statistical uncertainty arise from short tracks where the requirement of minimum # of 2D hits can cause DATA/MC discrepancy in track reconstruction

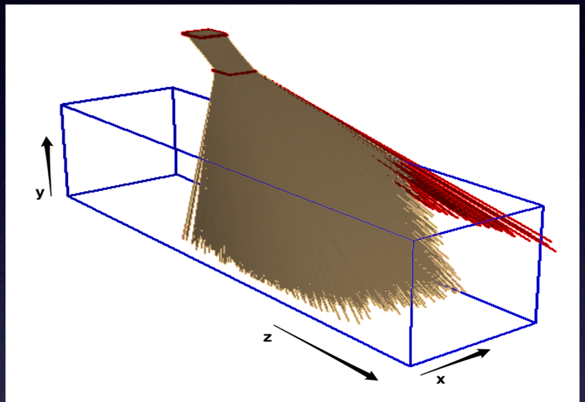
Space Charge Effect

Space Charge Effect Calibration

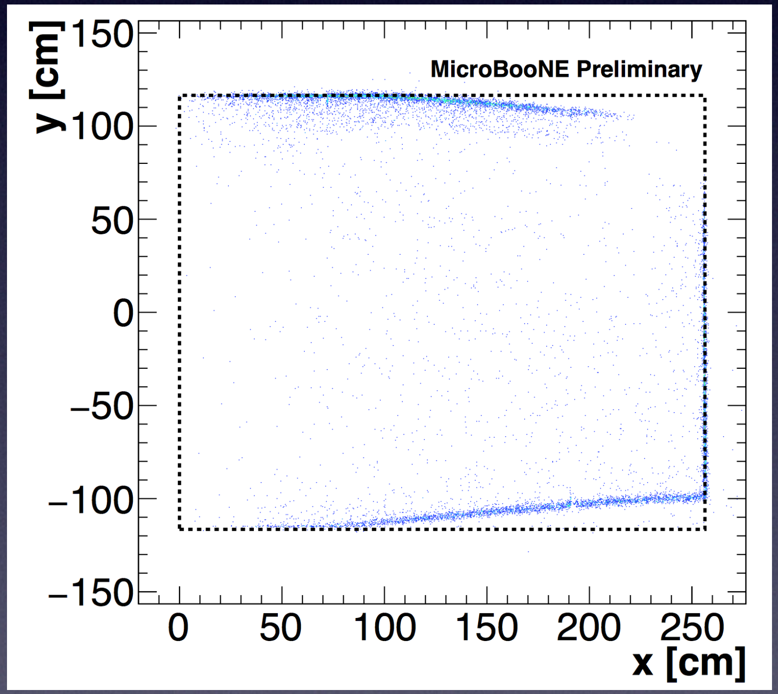


2D track can look rotated and/or curved due to SCE

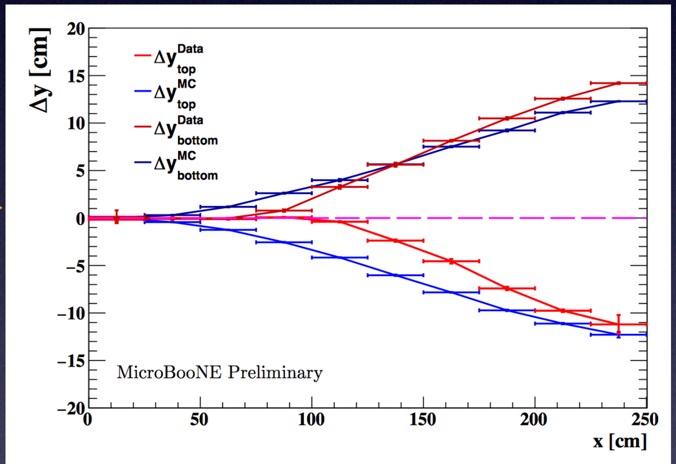
- Non-uniform E-field distorts reconstructed particle tracks
- Used external muon tracking system to study the effect



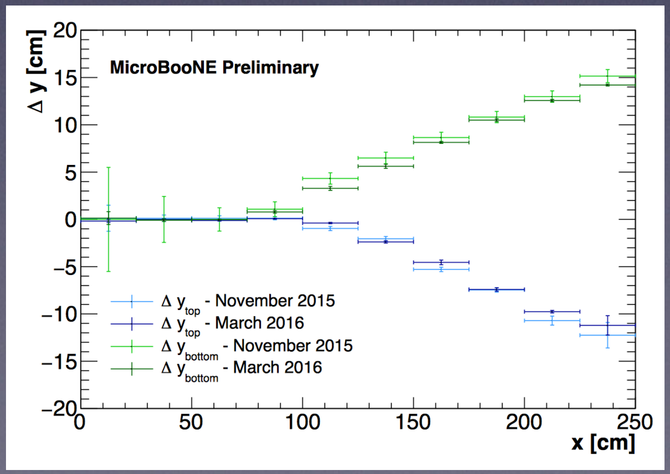
External Muon Tracker



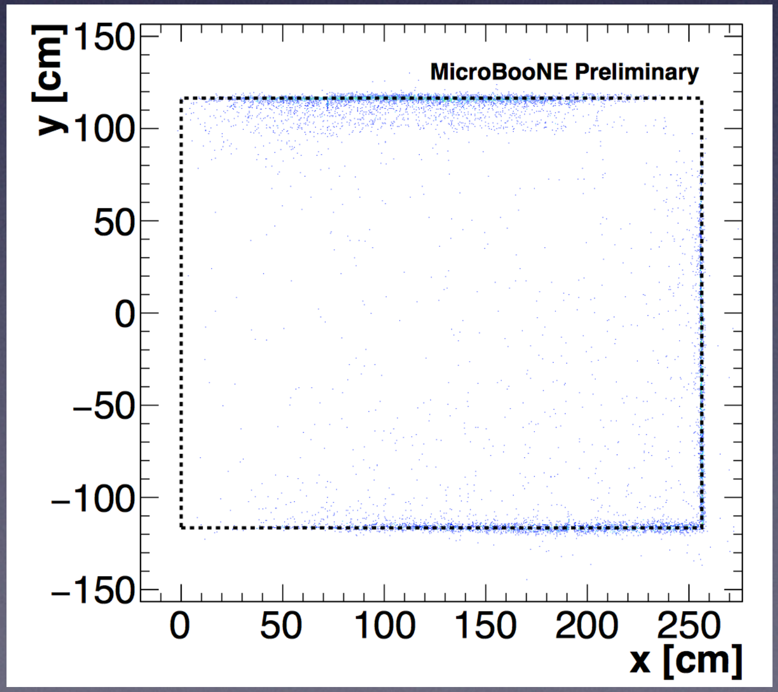
X-Y projection of 3D track start/end points



Simulation vs. Data Y distortion along X



Small time variation (Data)

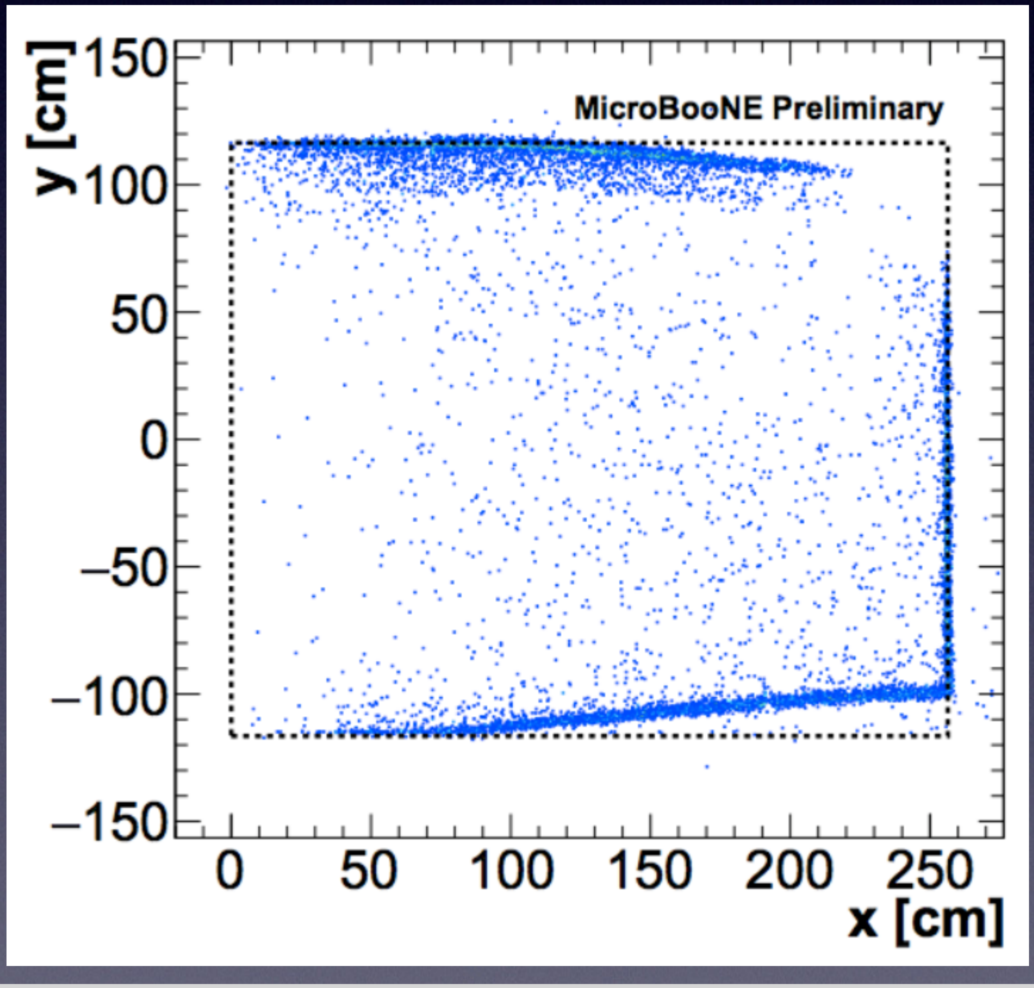


After correction

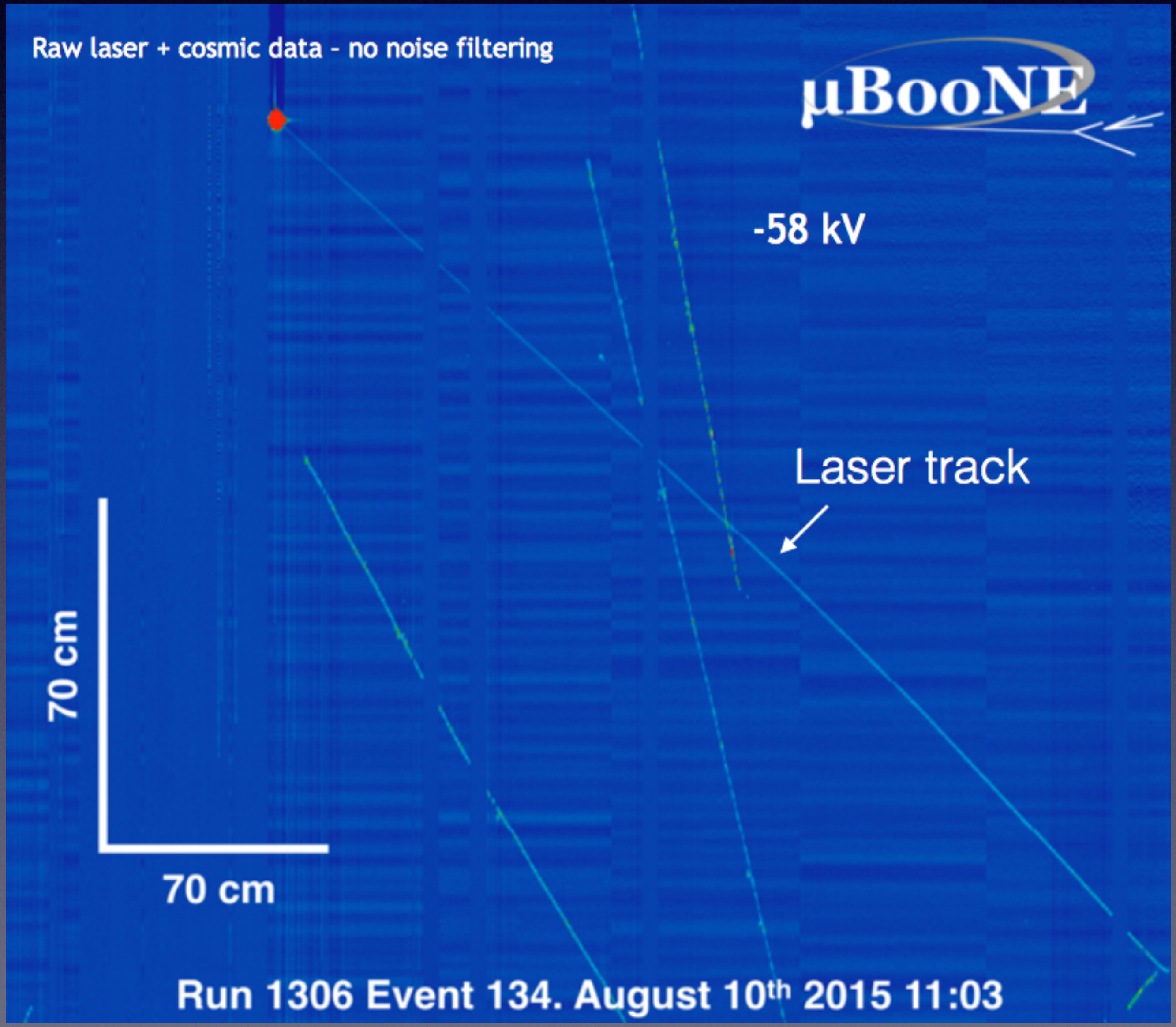
MicroBooNE Detector Physics

Space charge effect

- Positive ion build-up in the TPC, distorting local electric field
- Distorts the path of ionization electrons (i.e. track gets “bent”)
- Calibration importance for near-surface LArTPCs



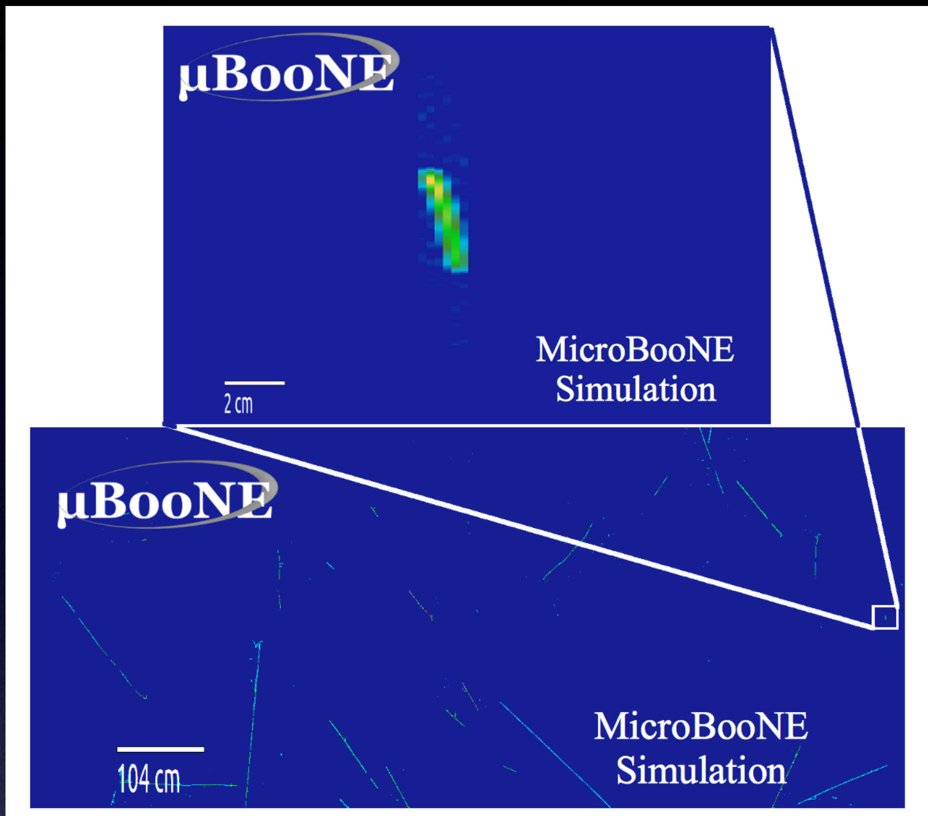
Space Charge Distortion
Through-going cosmic ray muon tracks’ start and end points in the side-slice of the detector. Distortion is due to space charge affecting the drift electric field



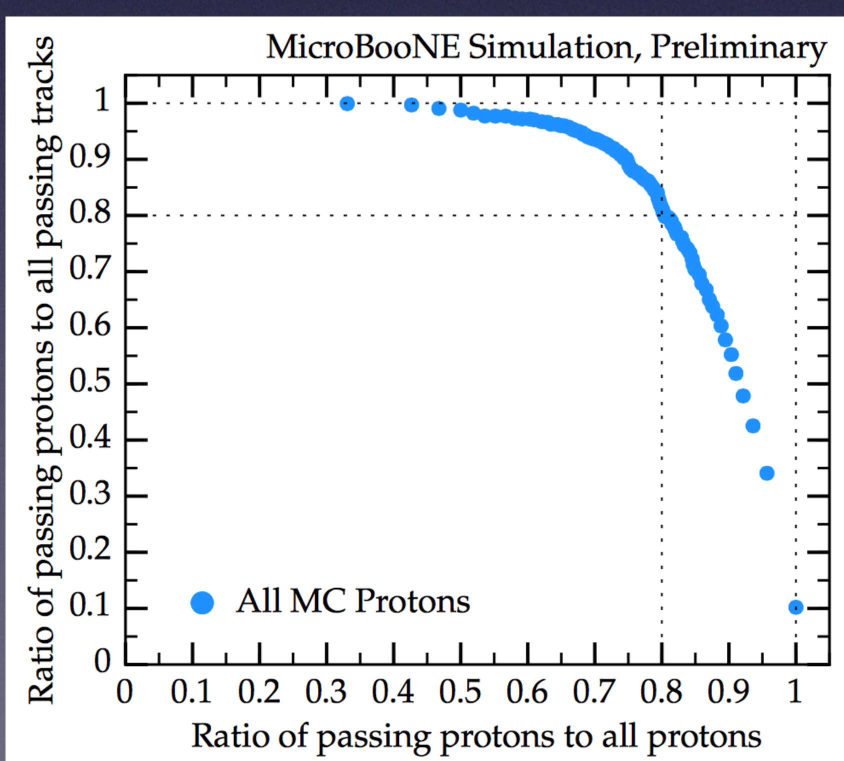
Laser calibration

NC Single Proton Search

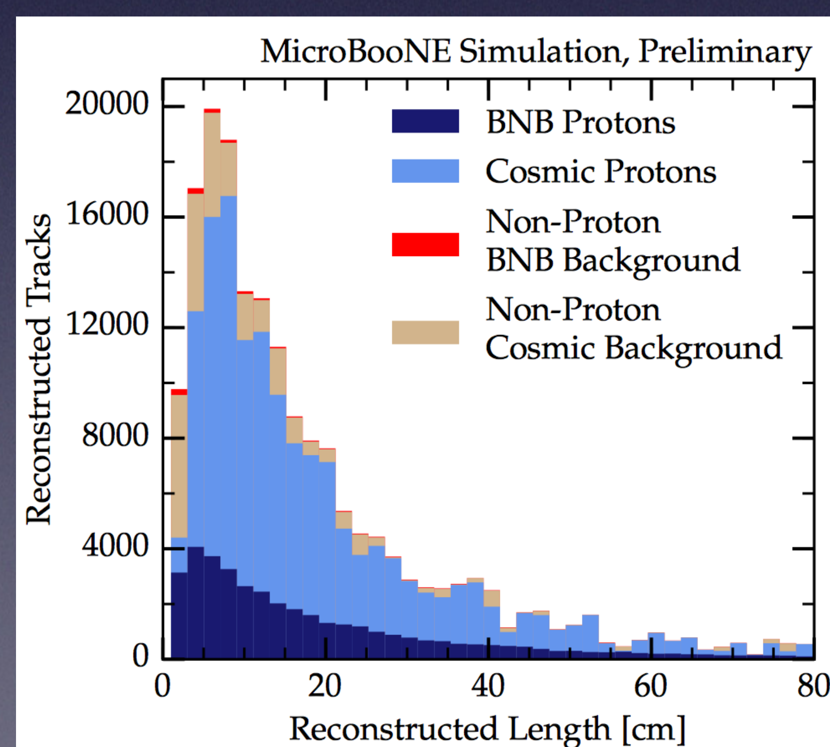
Identifying NC Proton Signal



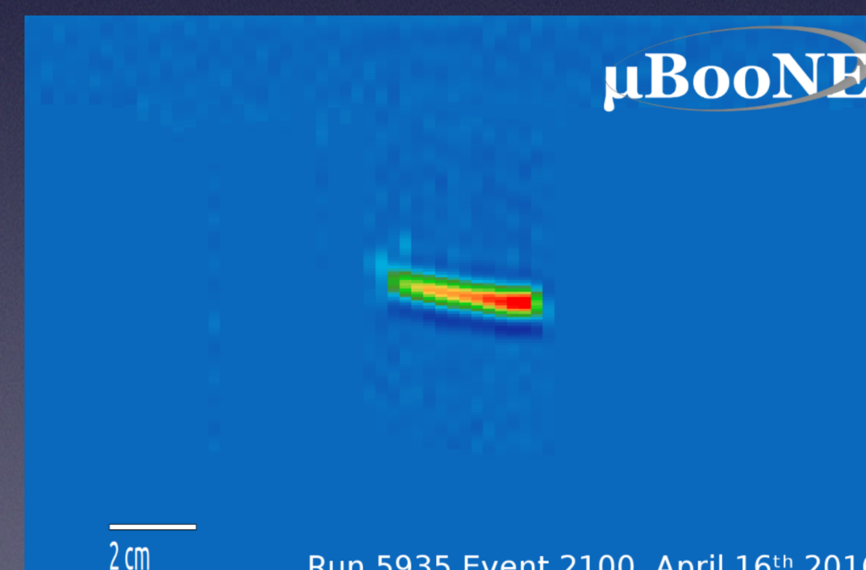
- Challenges
  - Very short proton tracks (~cm!)
  - High cosmic-ray backgrounds
- Boosted Decision Tree (BDT)
  - Use reconstructed track parameters as input variables



BDT Selection Efficiency vs. Purity



BNB + Cosmic (Simulation) Output Breakdown



Proton track candidate found by BDT (Real Data)

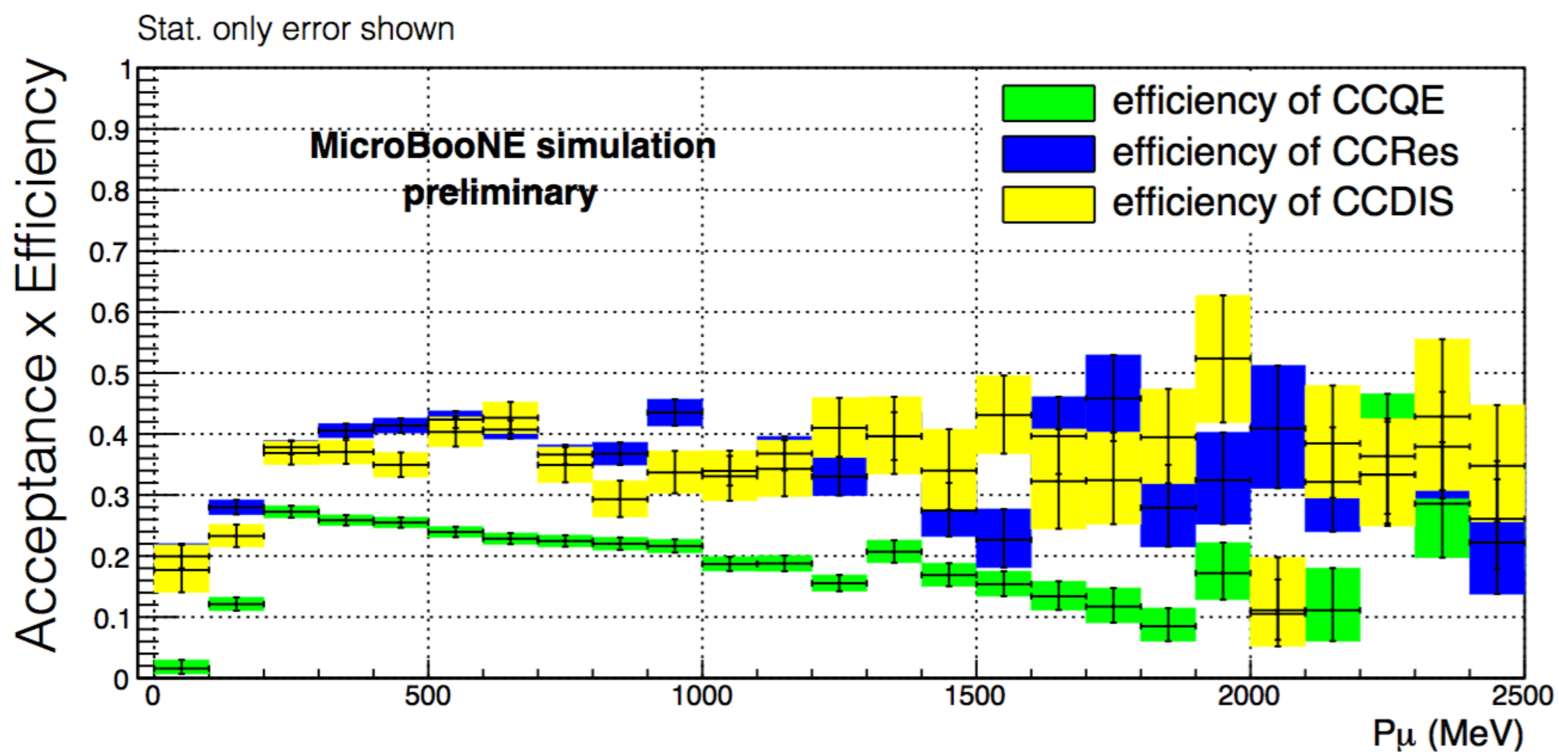
CC Selection

Fully Contained + Partially Contained Selection

- Purity: 65%
  - Cosmics are still the dominant background
- Acceptance x Efficiency: 30%
  - Containment and minimum length cut are applied to 1-track sample

Points to the challenge of operating a LArTPC on the surface

- Before selection:
  - 60% QE, 30% RES, 10% DIS
- After selection:
  - 43% QE, 42% RES, 14% DIS



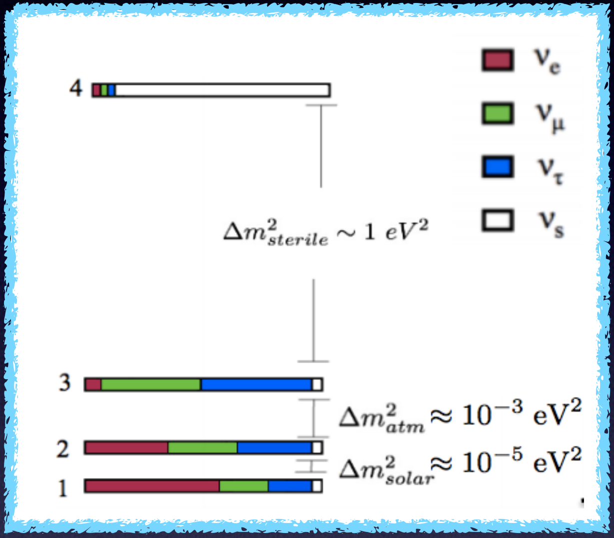
 From M. Toups @ Neutrino 2016

Oscillation Related

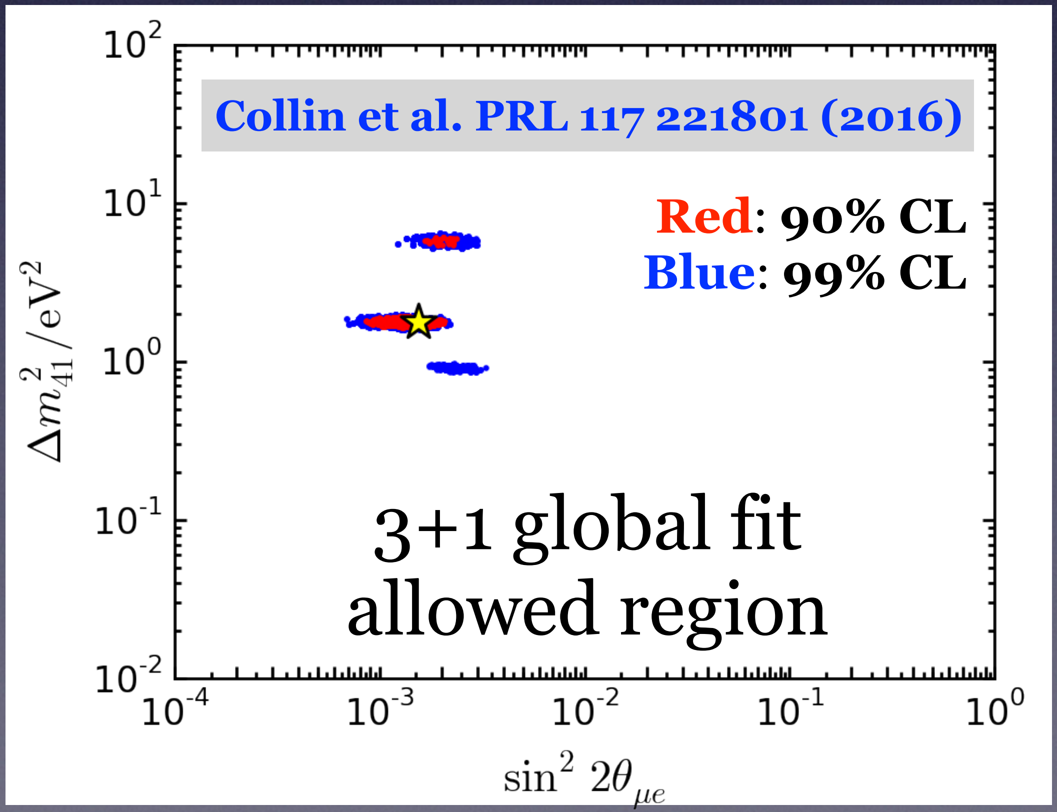
Status of "Anomalies"

Anomalies from appearance/disappearance

- Anomalies ≃ 2σ to 3σ level, each mass state must mix with each flavor state, even sterile
- Sterile neutrino oscillation must be seen in both appearance/disappearance



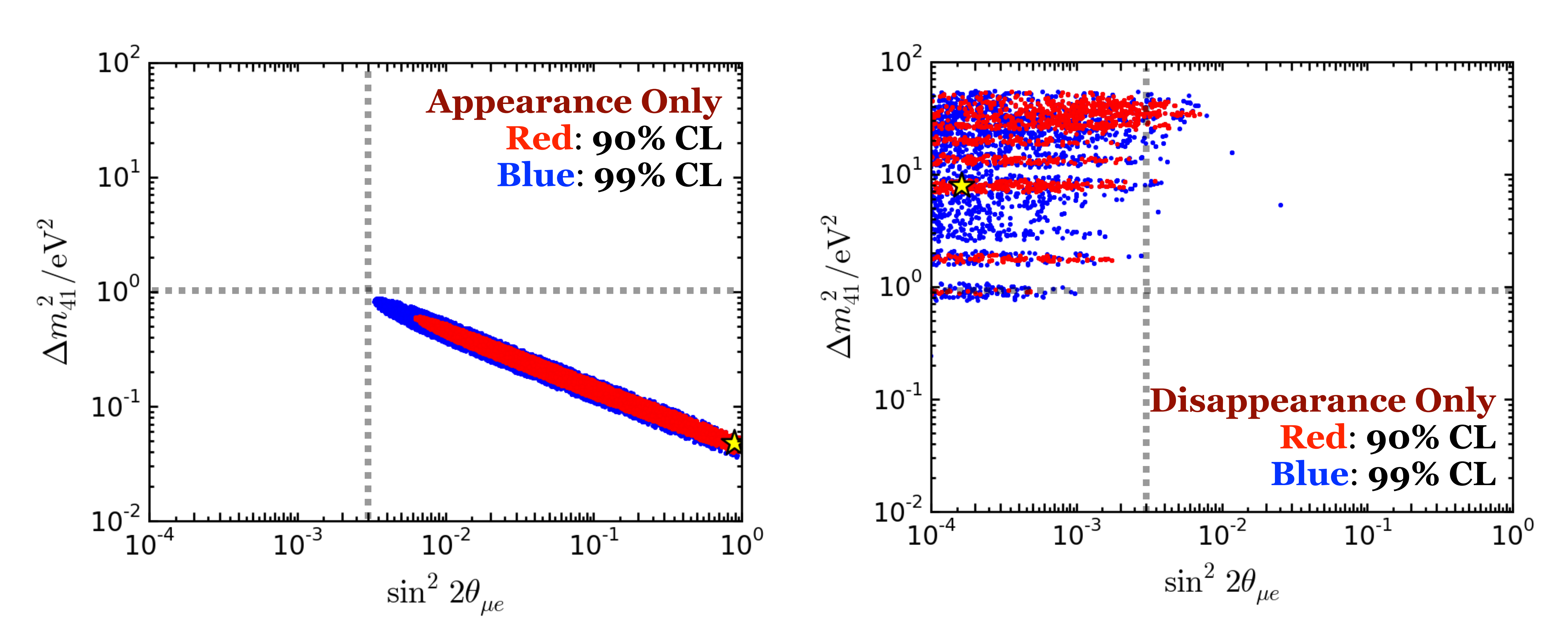
Experiment name	Type	Oscillation channel	Significance
LSND	Low energy accelerator	muon to electron (antineutrino)	3.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (antineutrino)	2.8σ
MiniBooNE	High(er) energy accelerator	muon to electron (neutrino)	3.4σ
Reactors	Beta decay	electron disappearance (antineutrino)	1.4-3.0σ (varies)
GALLEX/SAGE	Source (electron capture)	electron disappearance (neutrino)	2.8σ



3+1 Global Fit

Tension in appearance vs. disappearance

- Appearance/disappearance prefer smaller/larger Δm^2



3+1 Global Fit

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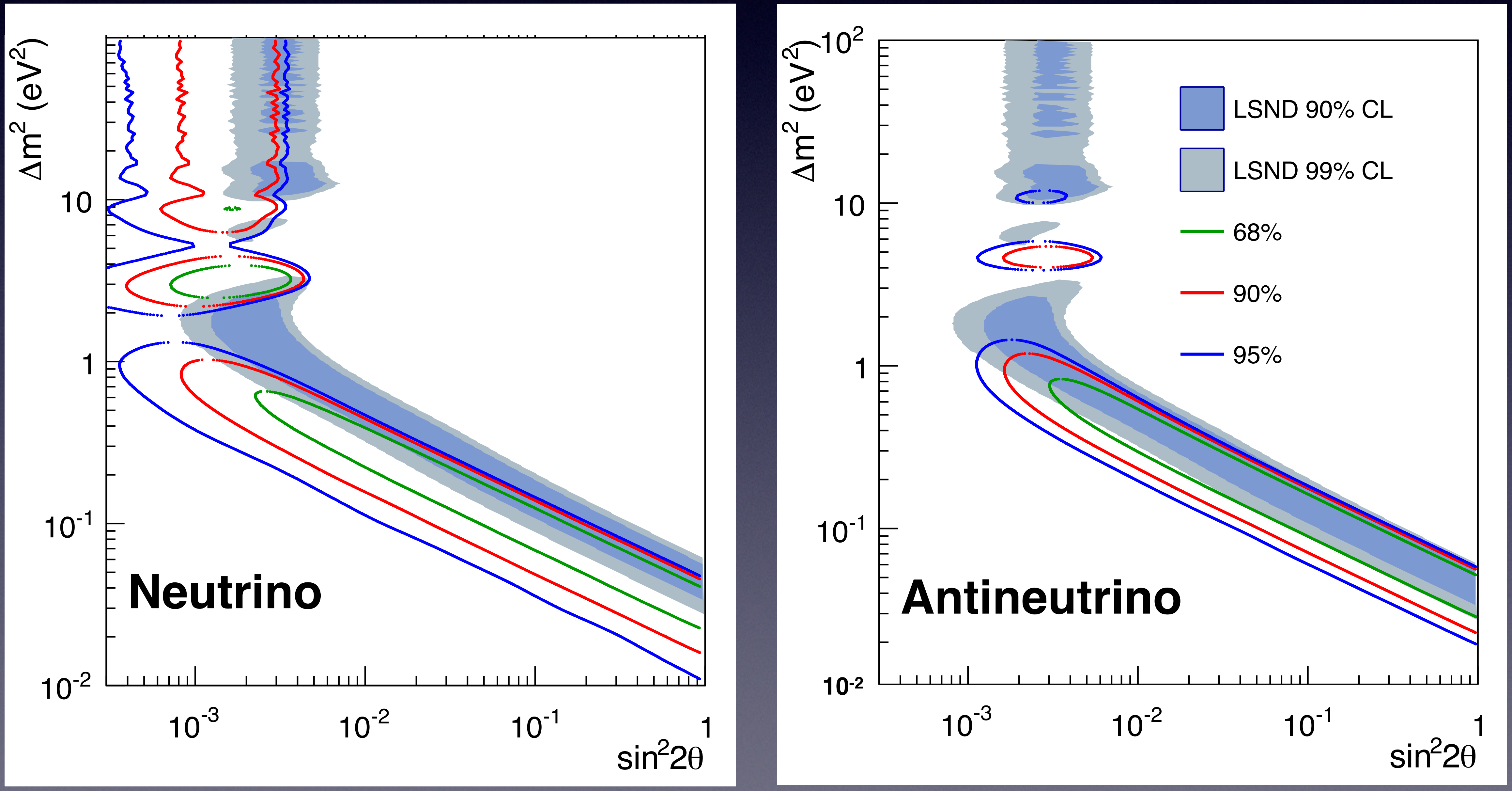
- MiniBooNE ν_e appearance favors low Δm^2, high $\sin^2 2\theta$



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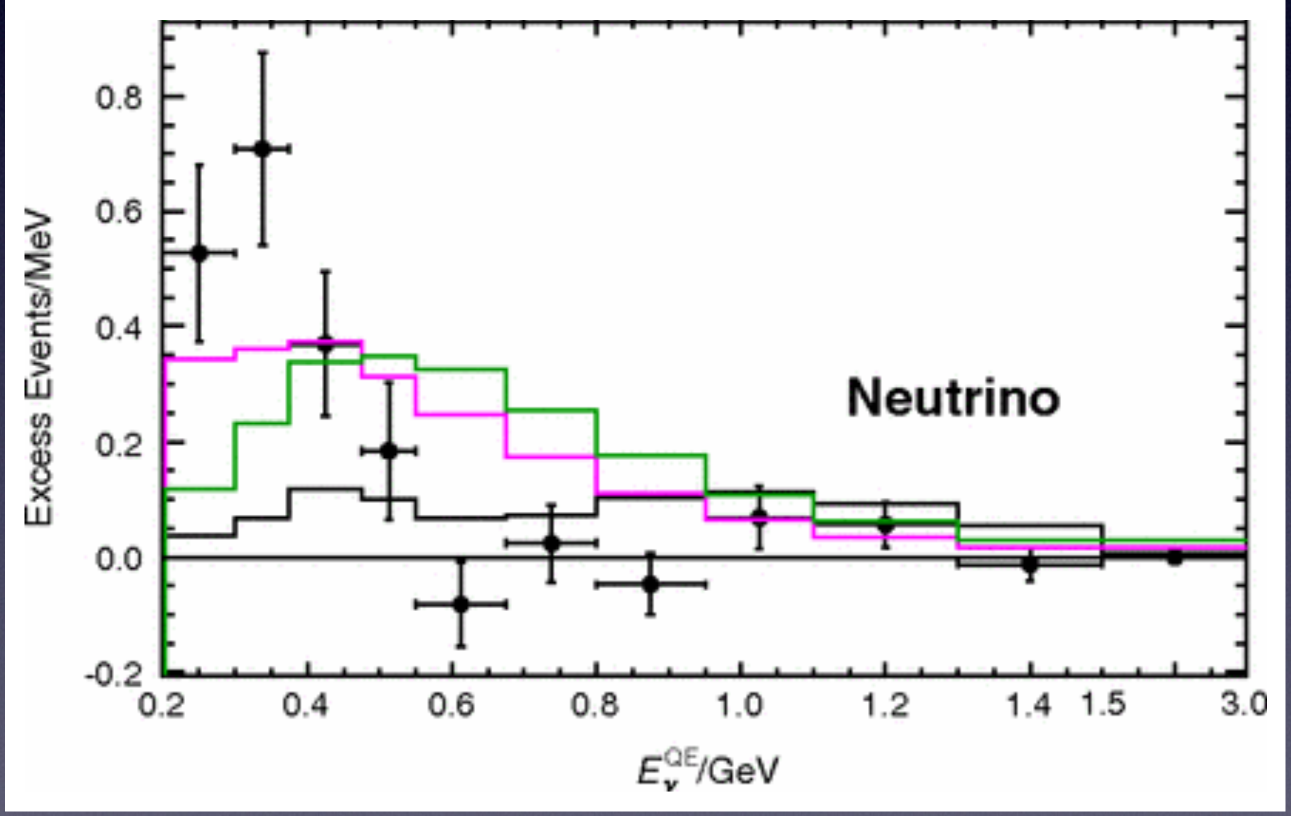
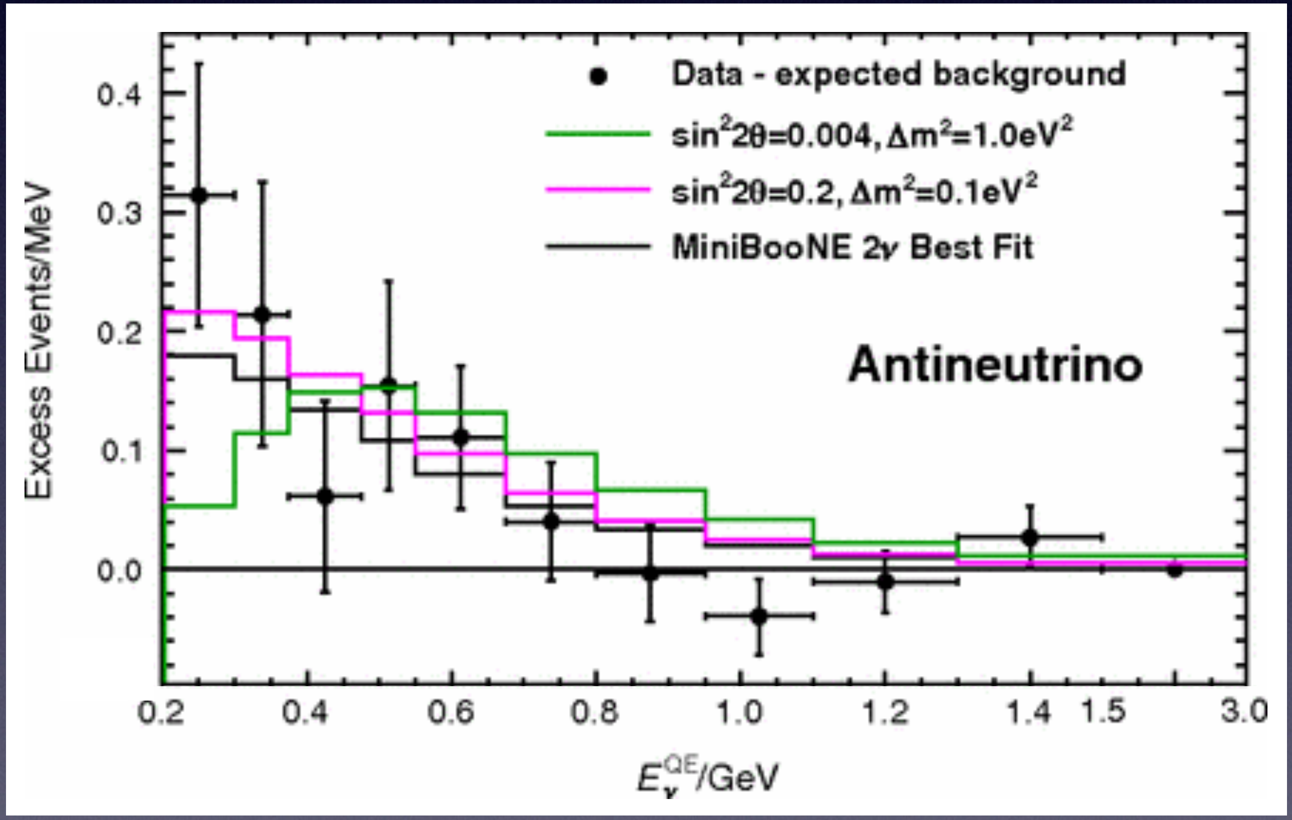




3+1 Global Fit

P. Huber (VT) @ APS 2017

Score card

	data	theory	no direct tension
LSND	0	+	-
MiniBooNE	+	- -	- -
T2K	+	- -	++
Gallium	+	++	++
Reactors	++	0	++

++ strong, + adequate, 0 undecided, - likely issue, - - clearly a problem

Discarding the MiniBooNE low-energy excess, a eV-scale sterile neutrino is a simple explanation for all the observations.

Understanding MiniBooNE is really important since it is standing out from the rest!

3+1 Global Fit

Possible outcomes from MicroBooNE

Case A: no excess
- 3+1 is in a trouble since it predicts signal @ MicroBooNE

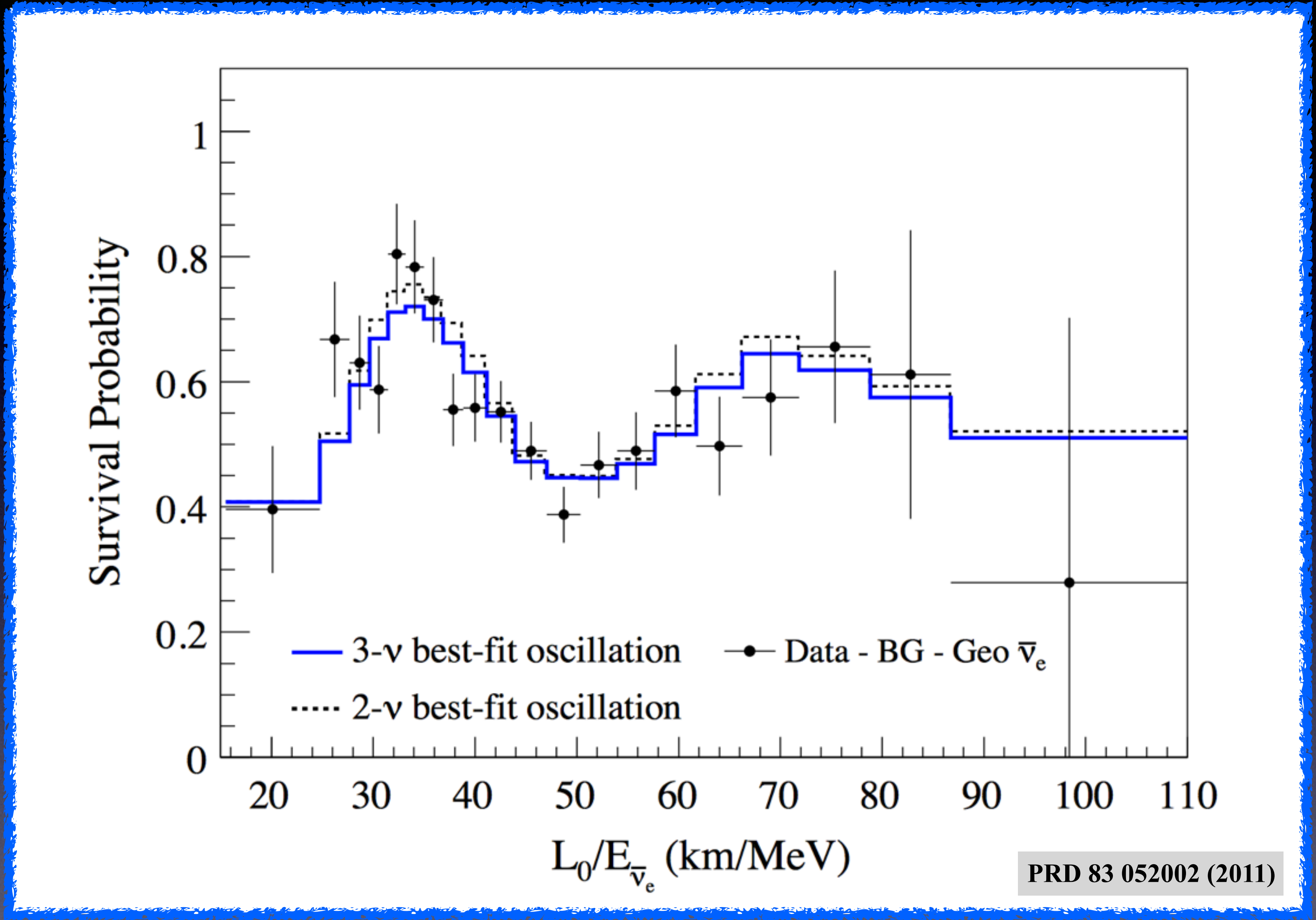
Case B: some excess but less than MiniBooNE at low energy
- 3+1 is strengthened, MiniBooNE result was likely affected by unaccounted γ background

Case C: same excess as MiniBooNE
- Picture is likely much more complicated than 3+1

Neutrino 2018 will be exciting!

Expect 1st results from appearance (MicroBooNE) and disappearance (reactor) experiments to meet!

Measuring Oscillation Pattern



From KamLAND experiment with

L ≃ 180 km observing survival probability of $\bar{\nu}_e$

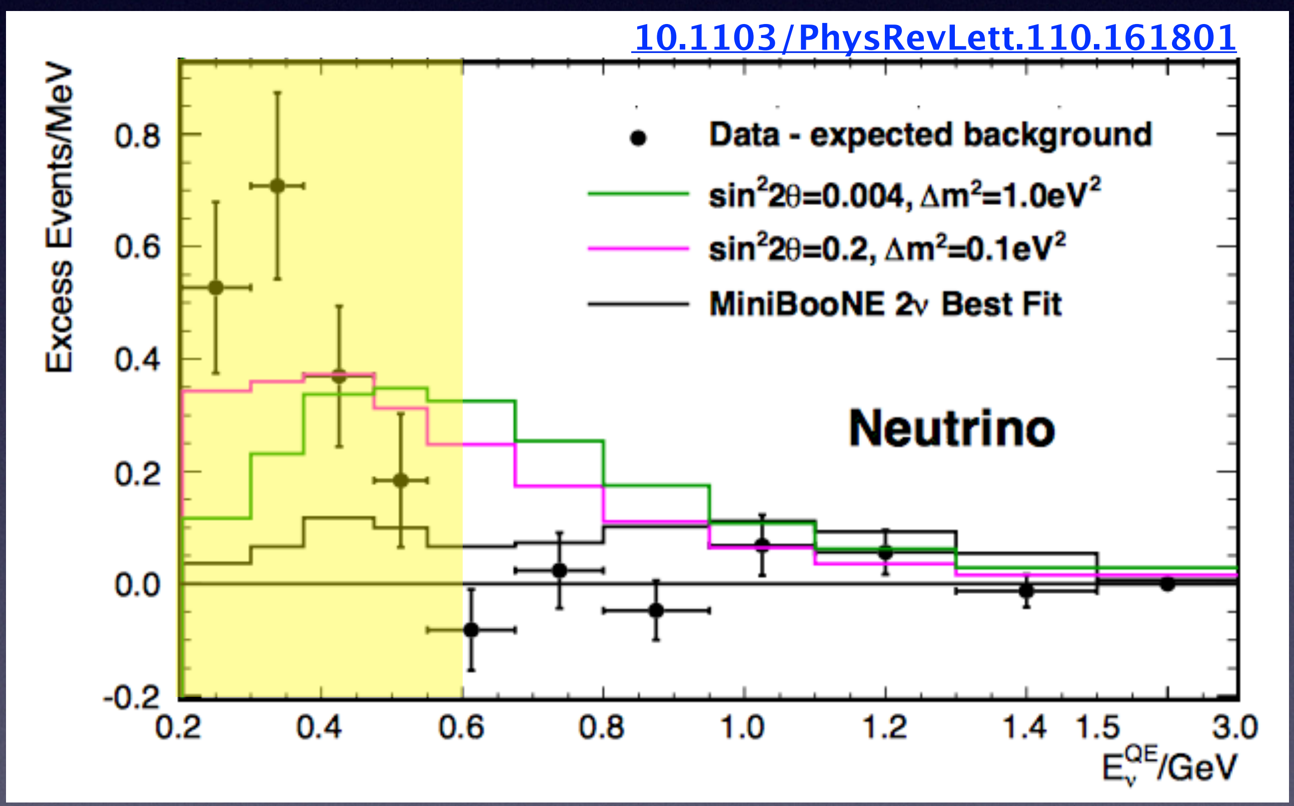
from nuclear reactor cores

MicroBooNE Oscillation Signal (I)

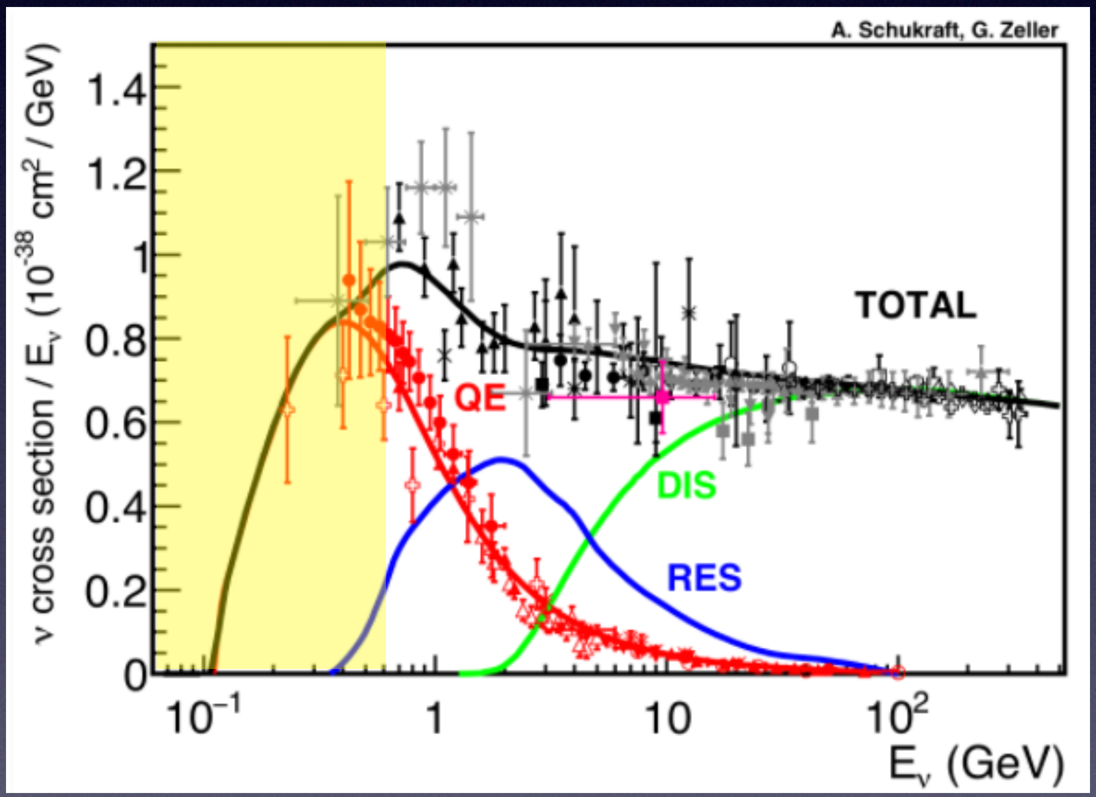
Goal: ν_e at low energy

Primarily 200 to 600 MeV neutrino energy

- Most of events have secondary particles contained inside the detector
- This is the region where CCQE interaction dominates



ν_e Low Energy Excess Fraction (MiniBooNE)



ν Cross Section (A. Schukraft, G. Zeller)

Low Energy Excess
LSND & MiniBooNE